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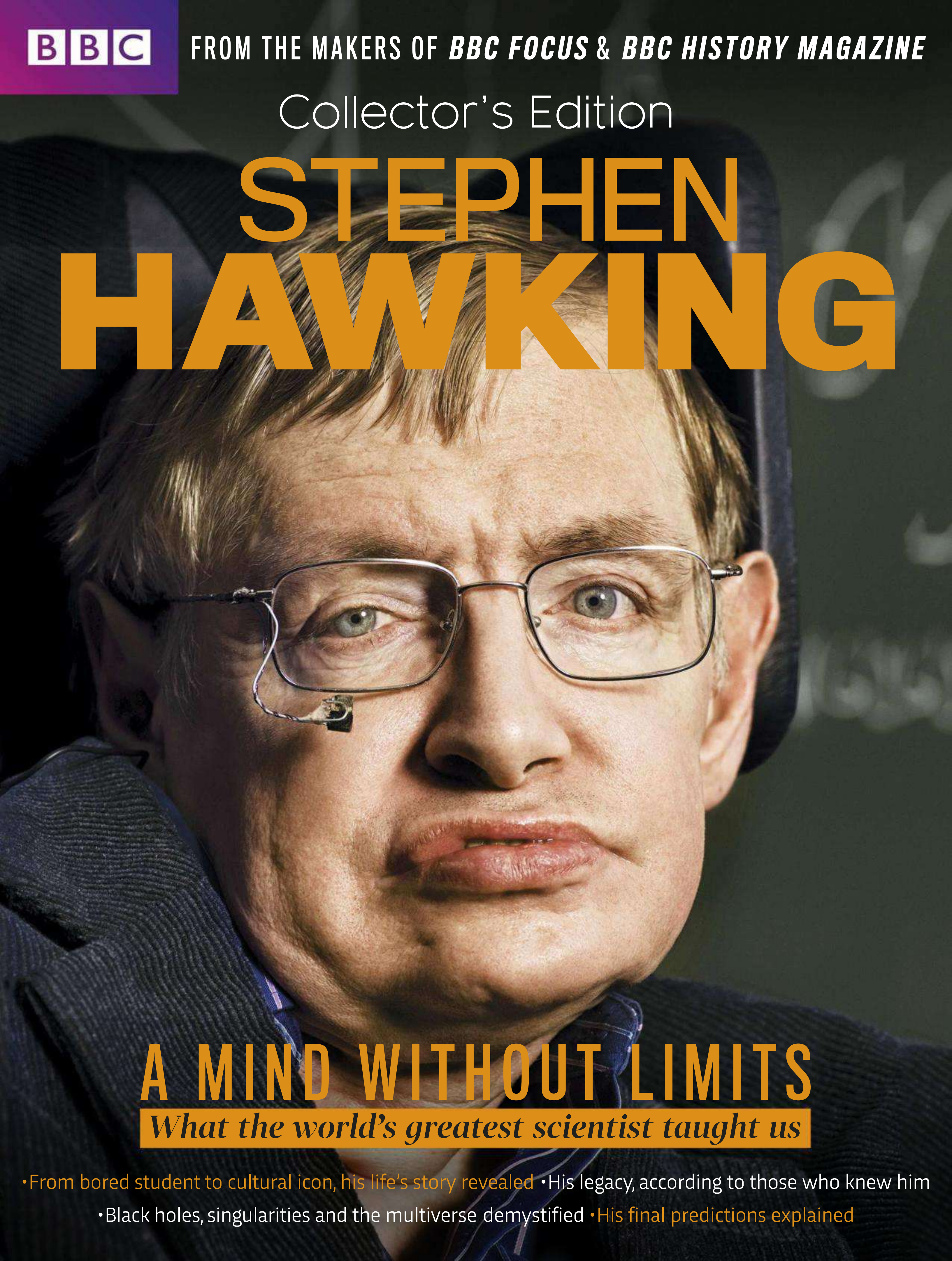
Collector's Edition

STEPHEN HAWKING



A MIND WITHOUT LIMITS

What the world's greatest scientist taught us

• From bored student to cultural icon, his life's story revealed • His legacy, according to those who knew him • Black holes, singularities and the multiverse demystified • His final predictions explained

ROYAL ALBERT HALL PRESENTS

IN MEMORY OF PROFESSOR

STEPHEN HAWKING

A BRIEF HISTORY

HIS WORK, LIFE AND LEGACY
IN DISCUSSION WITH SPECIAL GUESTS

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Welcome

Unyielding in the face of disease and the Universe

The world has lost a giant. Prof Stephen Hawking, the Galaxy's best-known scientist and most unlikely cultural icon, died on Wednesday 14 March at his home in Cambridge. I've spent the days since speaking to those who knew him and one clear theme emerges. Hawking was a stubborn man. Of course, he was funny and smart, that was clear for the world to see. But perhaps, to those of us watching from afar, his radiance hid the vital ingredient to his genius: true grit.

Hawking was determined to never let his condition slow him down. Sometimes literally: Hawking broke his leg on his 60th birthday after driving too fast off a kerb. He travelled the world, and even had a taste of zero-gravity.

It was this same resolve that would drive him, sometimes to the exacerbation of his colleagues, to spend years writing and rewriting his books so that he could share the elegance of the Universe with others. And ultimately it was this sheer strength of will, rather than a single eureka moment, that would propel him through the maths that underlined his work. Funnily enough, Hawking shared this personality trait with the most famous scientist of the last century, Einstein, who wrote of himself: "If I have a gift, it is that I am as stubborn as a mule." So if you learn anything from Hawking, I suggest that it needn't necessarily be the nature of black holes or the origins of singularities, but that sometimes a little stubbornness can be a useful thing.

Daniel Bennett, Editor

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COVER : GETTY

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HAYLEY BENNETT
Science writer Hayley explores the pathology of motor neurone disease and outlines the challenges posed by diagnosing and treating it.

PETER J BENTLEY
A Professor of computer science at University College London, Peter delves into the technology that enabled Hawking to keep talking.

MARCUS CHOWN
Marcus, an author and former radio astronomer, guides you through the theories and writings that characterised Hawking's life.

BRIAN CLEGG
Award-winning science author Brian delves into optimism and pessimism inherent in Hawking's outlook for the future of humanity.

CHARLOTTE SLEIGH
Prof Charlotte Sleigh examines how the achievements of Britain's greatest scientific minds' stack up against Hawking's accomplishments.

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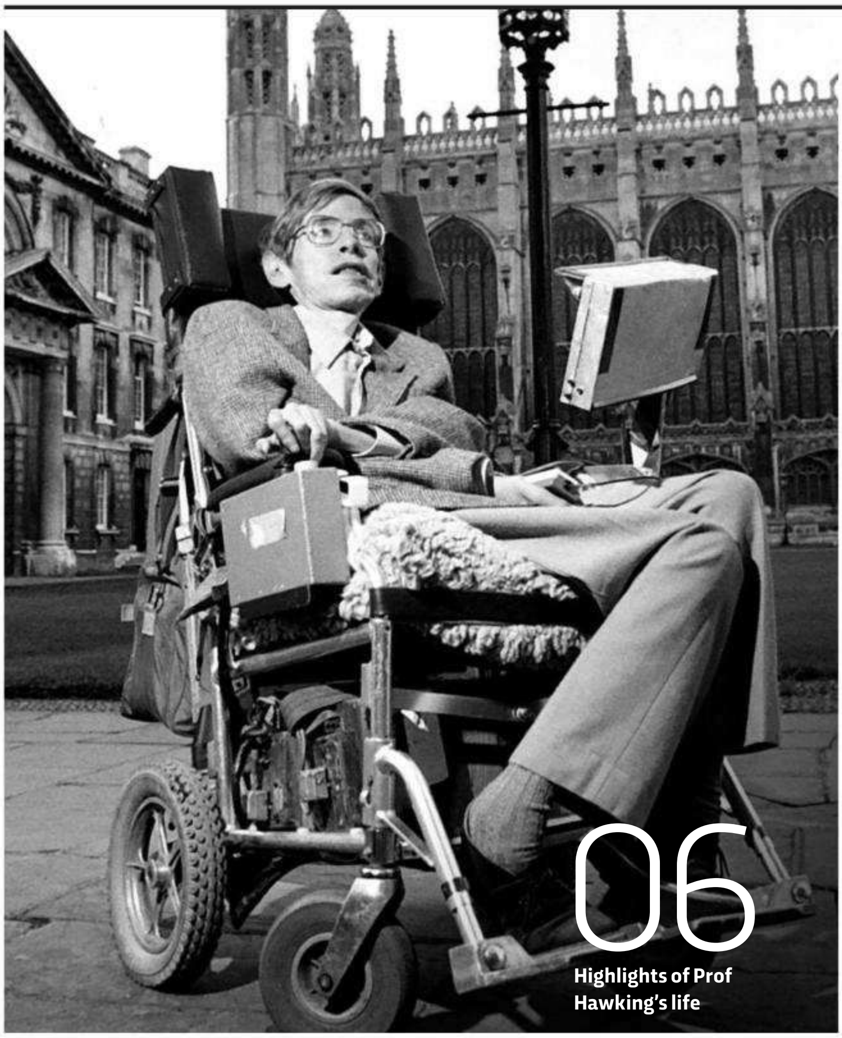

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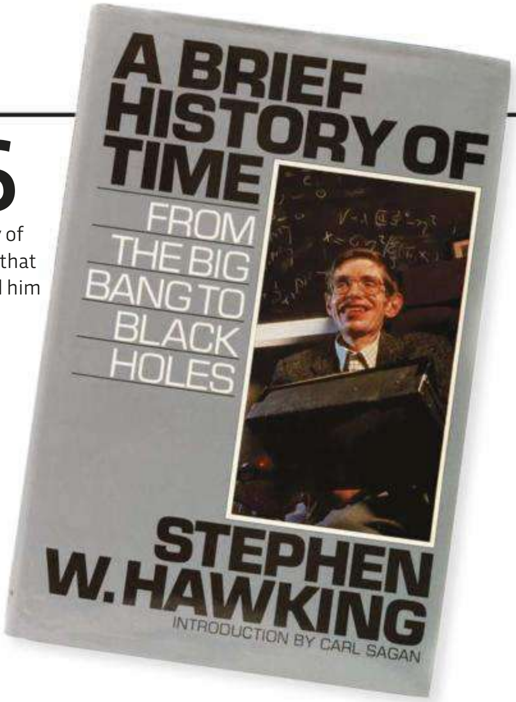

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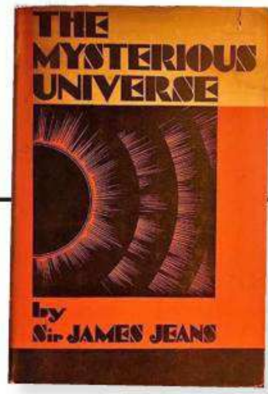

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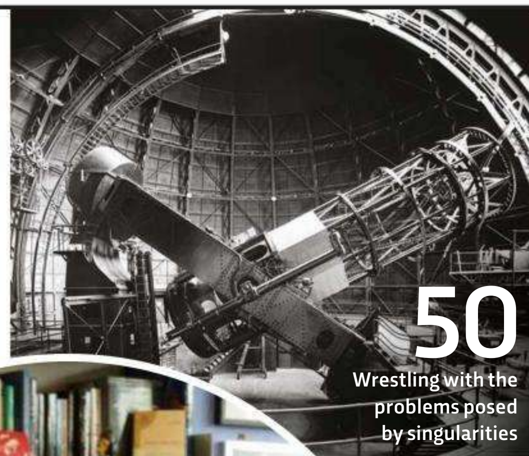

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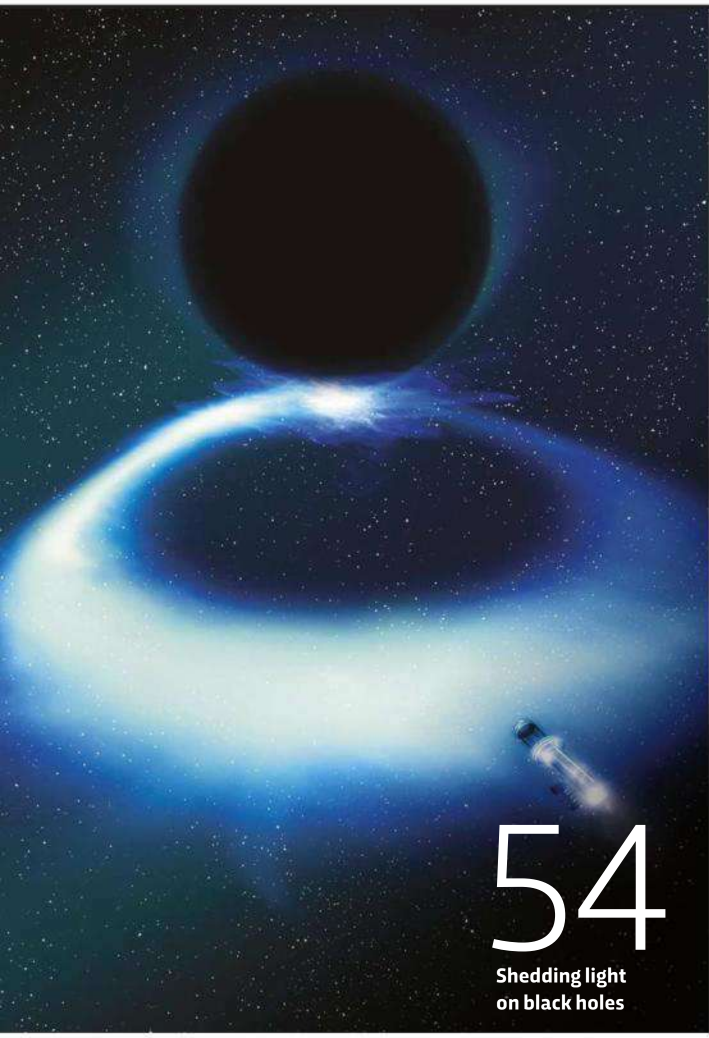

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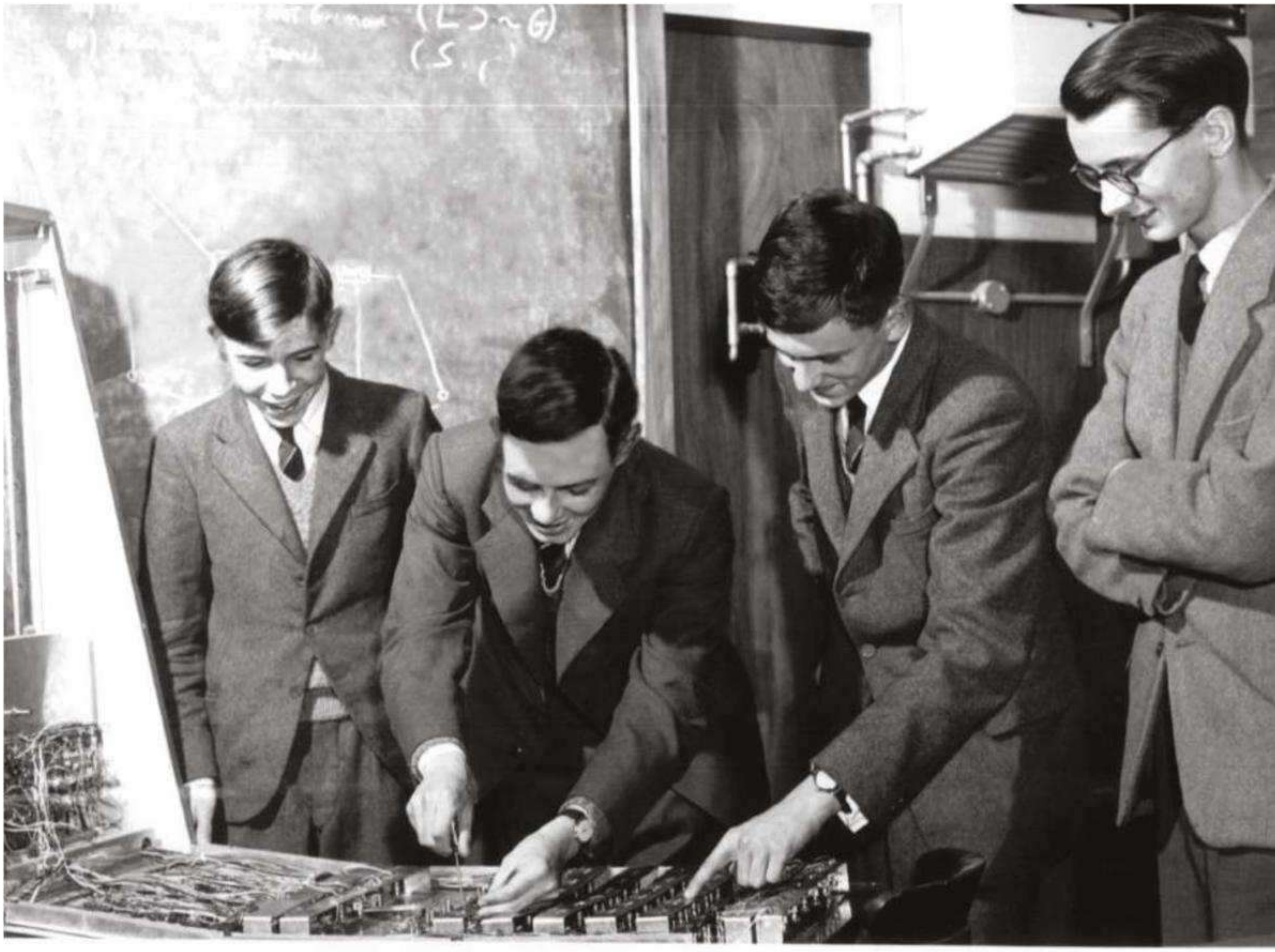
MORE THAN A SCIENTIST

Told at the age of 21 he had just two years left to live, Hawking's life defied expectation in every sense. Here we chart the life of science's brightest star

WORDS: **RUSSELL DEEKS**

IN THE BEGINNING
Stephen Hawking was born in Oxford on 8 January 1942. The oldest of four siblings, a young Hawking is pictured here with his sister Mary.

THREE OF A KIND
With sisters Mary and Phillipa as a young boy. In 1955, parents Frank and Isobel adopted a fourth sibling, Edward.



SCHOOL DAYS, 1958
While attending the private St Albans school, a 16-year-old Hawking (left) and his friends built a working computer using parts salvaged from clocks and an old telephone switchboard.

THE GRADUATE, 1963
Hawking graduated from University College, Oxford with a first-class honours degree in natural sciences in 1962. He then moved to Cambridge to take up post-graduate research at Trinity Hall, but his future was thrown into doubt when, early in 1963, he was diagnosed with amyotrophic lateral sclerosis (ALS), the most common form of motor neurone disease.

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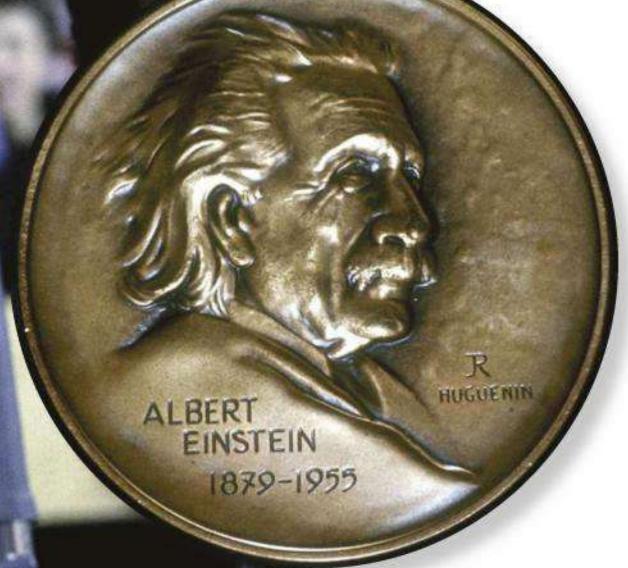
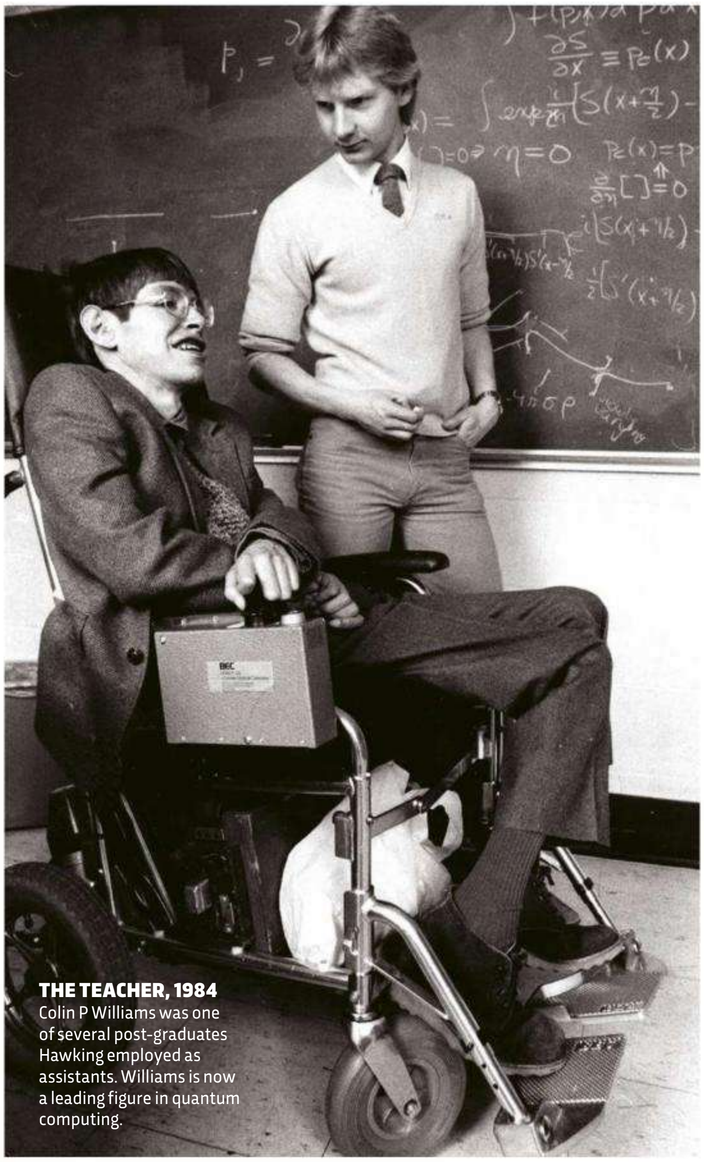
FAMILY MAN, 1978
Hawking with his first wife, Jane, and his children Robert and Lucy. The couple's third child, Timothy, was born the following year.



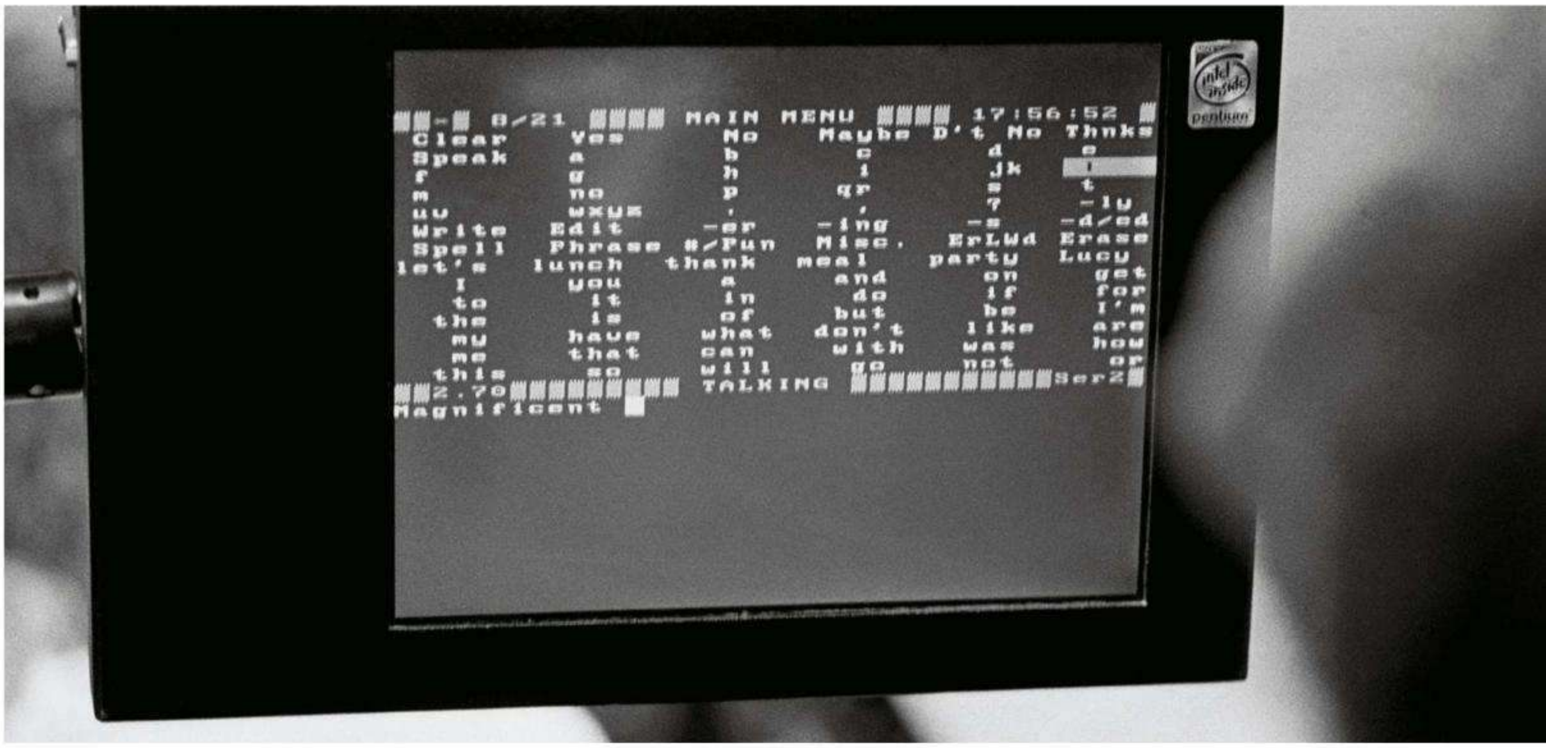
GOING FOR GOLD, 1979
In 1979, Hawking became the first recipient of the Albert Einstein Medal, awarded annually for groundbreaking work inspired by Einstein's own.

MEETING OF MINDS, 1988
Hawking with physicist, astronomer and writer Arthur C Clarke (left) and *Mastermind* presenter Magnus Magnusson (right) on the set of the TV show *Masters Of The Universe*.



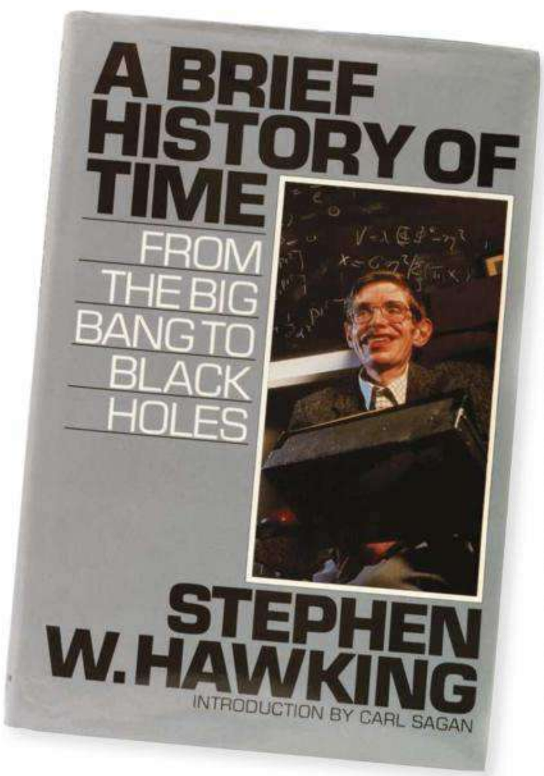
THE TEACHER, 1984
Colin P Williams was one of several post-graduates Hawking employed as assistants. Williams is now a leading figure in quantum computing.

TOPFOTO, GETTY X3, SHUTTERSTOCK



SPEAKING OUT
In 1985, a bout of pneumonia left Hawking in need of a tracheotomy that robbed him of his voice. From that point onwards, he communicated via a series of increasingly sophisticated computer devices. Later on, he insisted on keeping the early device's robotic American voice that he had become known for, even though more realistic voices had become available.

KEEP IT BRIEF, 1988
Hawking began working on a popular science book in 1982 with a view to supplementing his academic income. After years of editing and rewrites, *A Brief History of Time* was eventually published in 1988 and would go on to become a global bestseller, making its author a household name.



THE PROFESSOR, 1988
At the University of Cambridge, where Hawking was Lucasian Professor of Mathematics from 1979-2009 – a post formerly held by both Isaac Newton and Charles Babbage.

GENIUS AT WORK
Hawking in his office at the University of Cambridge in the late 1980s.

MR PRESIDENT, 1998
Hawking talking about the future of science with US President Bill Clinton at the White House, 6 March 1998.

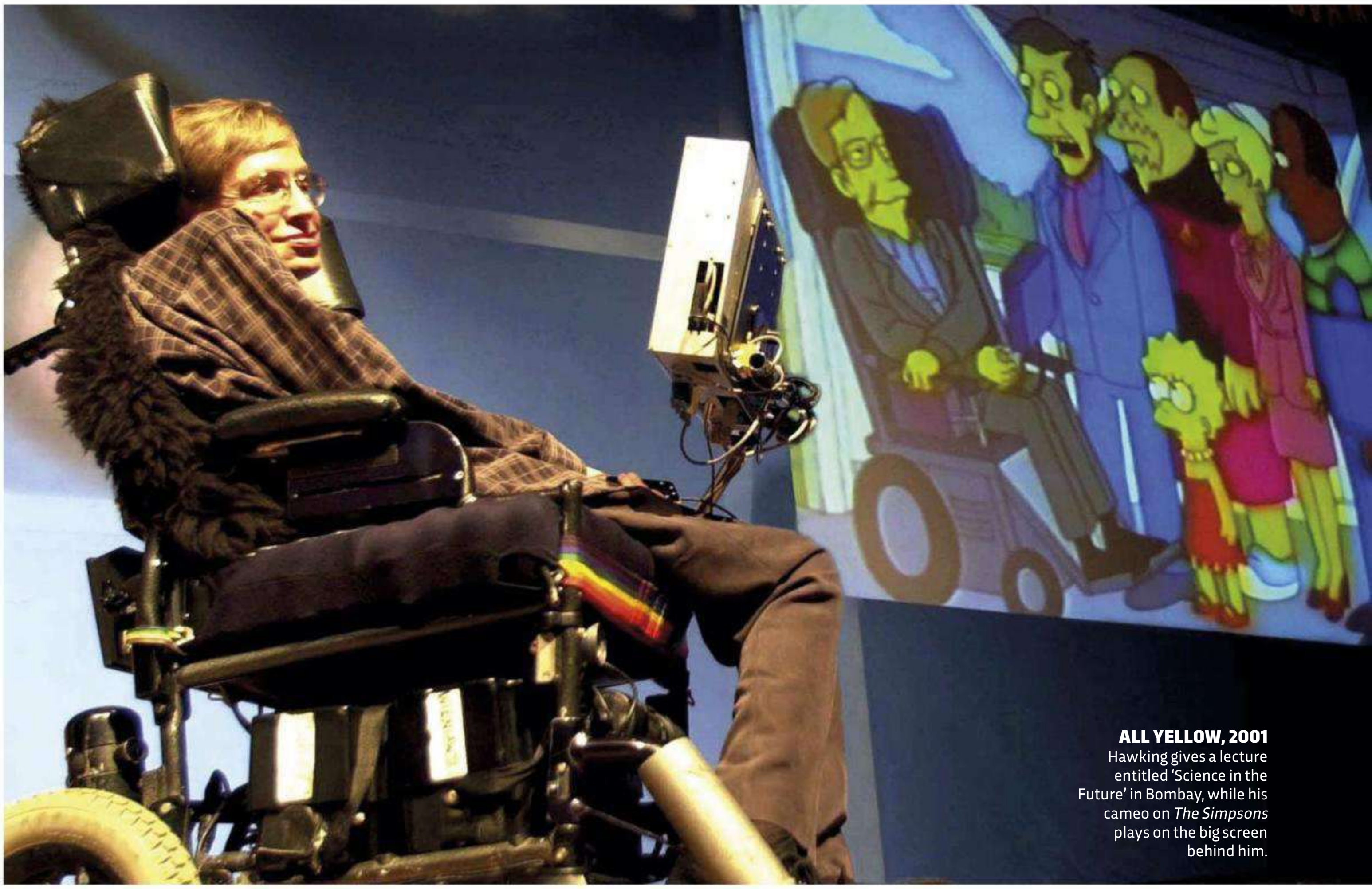
STAR TREKKING, 1993
Hawking played a hologram of himself in an episode of *Star Trek: The Next Generation,* where he took part in a game of poker with the android character Data and holographic renditions of Einstein and Newton.

BAZINGA!, 2012
With *The Big Bang Theory* star Jim Parsons who plays Sheldon Cooper. Hawking appeared in no fewer than six episodes of the sitcom.

ALAMY X4, GETTY X3

BRIDE & GROOM, 1995
With second wife Elaine Mason, who had formerly been his nurse, at their wedding in Cambridge. The couple divorced in 2006.

GEEK CHIC, 1997
With Microsoft founder Bill Gates at the University of Cambridge, where Gates had just donated $80 million (£56m) to set up a new research centre.



ALL YELLOW, 2001
Hawking gives a lecture entitled 'Science in the Future' in Bombay, while his cameo on *The Simpsons* plays on the big screen behind him.

MOVIE STAR, 1991
Errol Morris's 1991 film *A Brief History of Tim*e was the first movie version of Hawking's life, with the central characters playing themselves.

LIFT-OFF, 2007
On 26 April 2007, Hawking experienced weightlessness when he took a flight on a jet operated by the Zero Gravity Corporation. The look on his face says it all...

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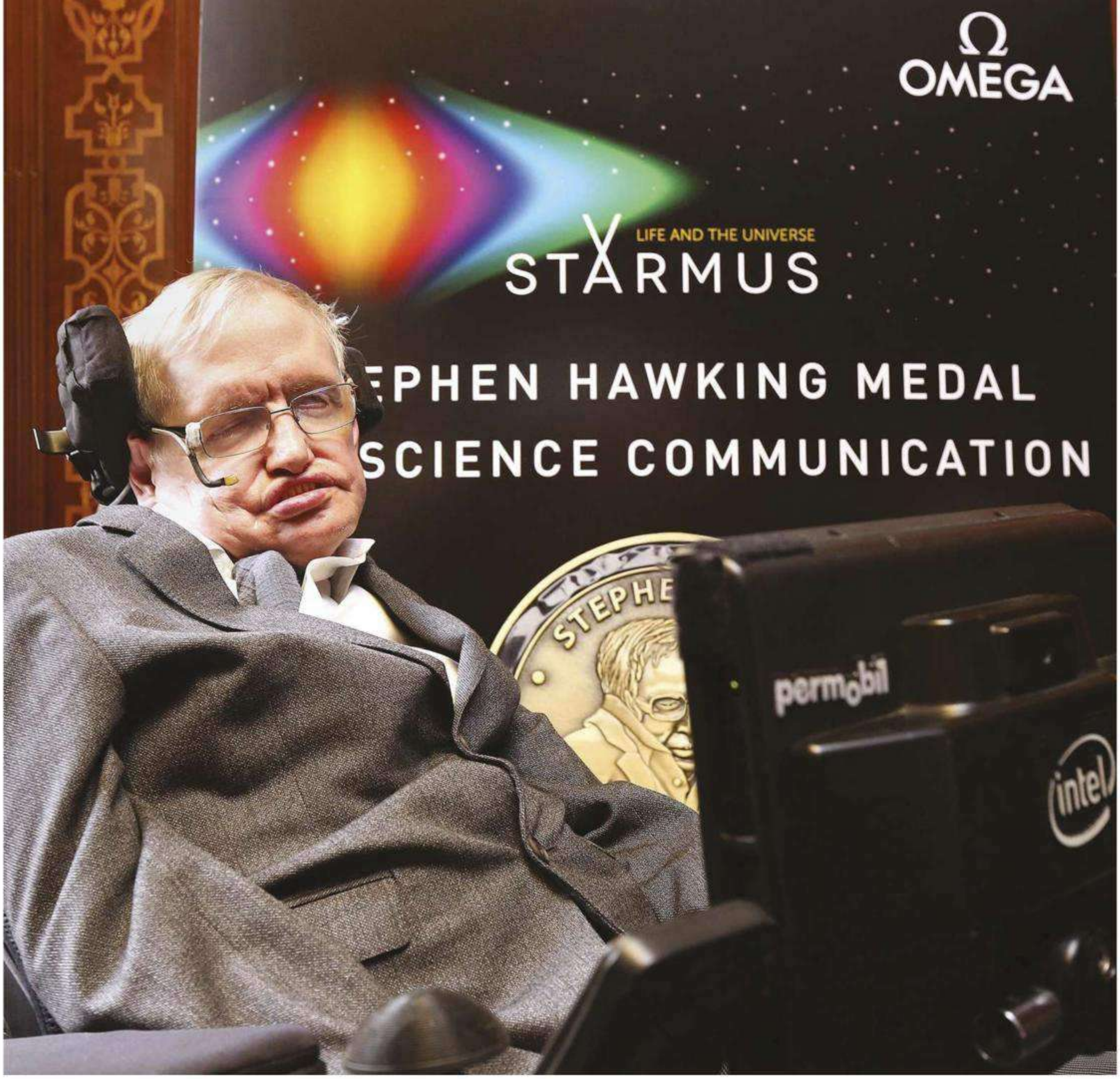
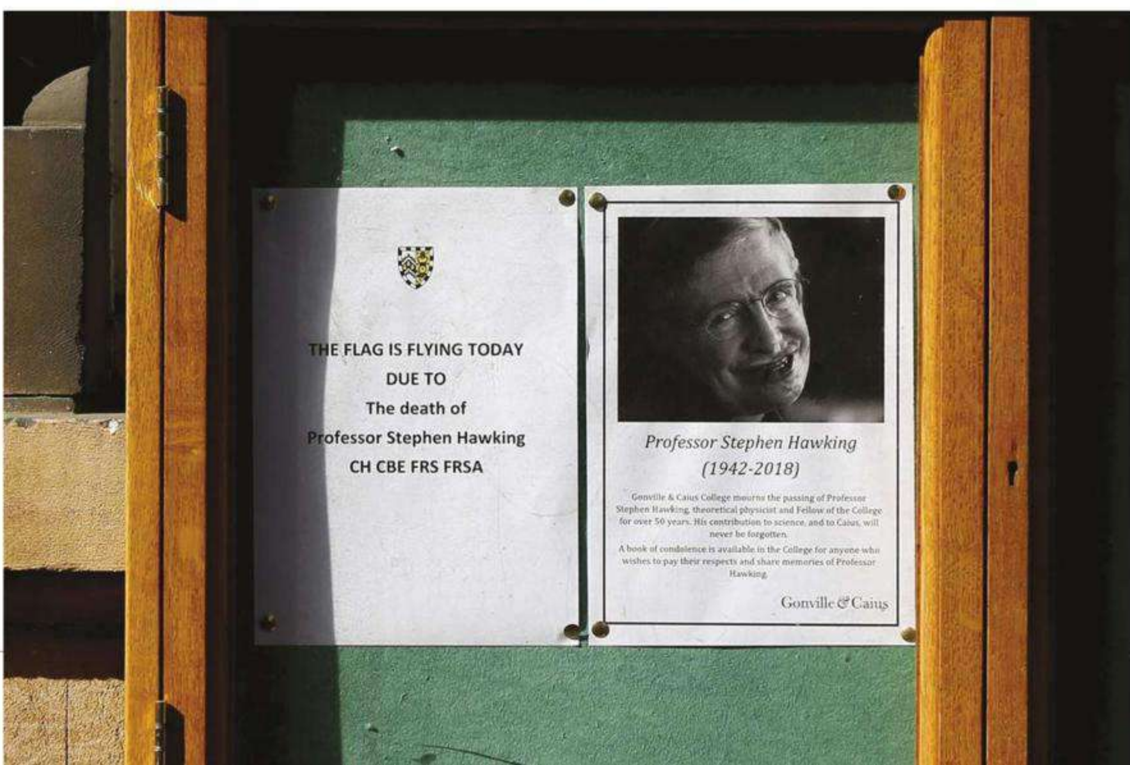
JOHANNESBURG, 2008
Hawking meets former South African president Nelson Mandela. He was in the country to help establish new research centres, using $75m (£53m) donated by technology giants.

BLUE RIBBON, 2009
Receiving the Presidential Medal of Freedom from President Barack Obama. The medal is the highest honour that can be awarded to a civilian in the US.

ROYAL CONNECTIONS, 2014
Hawking meets Queen Elizabeth II during a reception at St James's Palace for a disability charity.





PAY IT FORWARD, 2016
In 2016, Hawking launched the Stephen Hawking Medal, for people working in the arts whose work has helped to enhance the public's understanding of science.

THE END, 2018
How news of Hawking's death was officially broken to students at Gonville & Caius College, Cambridge, where he had been a Fellow since 1967.

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Part One

HAWKING'S LIFE

Despite spending most of his years dealing with a condition that took his ability to walk and later his ability to talk, Hawking refused to let motor neurone disease define his existence. He stubbornly pursued a personal life as rich and varied as his professional one

Hawking's Life Story – FROM OXFORD TO CAMBRIDGE AND BEYOND P18

A Brief History of Time – THE STORY OF HIS LANDMARK BOOK P26

Saving Stephen's Voice – HUMAN THOUGHT, COMPUTERISED SPEECH P34

Life With ALS – DIAGNOSIS AND TREATMENT P41

ANDRE PATTENDEN


intel

HAWKING'S LIFE STORY

A look back at the personal life and career of one of Britain's greatest ever scientific minds

WORDS: **MARCUS CHOWN**

Stephen Hawking was one of the most imaginative and influential physicists of his generation – yet he never won the Nobel Prize. He wrote a popular science book that became a publishing sensation – but which is arguably the least-read bestseller of all time. He was cruelly confined to a wheelchair by a disease that progressively paralysed him – yet his mind ranged freely across the immensities of the cosmos. These are just some of the paradoxes of what, by any standards, was an extraordinary life.

Hawking was born in Luftwaffe-ravaged London on 8 January 1942, exactly 300 years after the death of Galileo (a fact that greatly appealed to him). Though his father wanted him to be a doctor, he was inspired by a schoolteacher to study physics at the University of Oxford, where he was, by his own admission, a rather lazy student. From there, he moved to the University of Cambridge to study for a PhD, in the then-unfashionable field of general relativity, Albert Einstein's theory of gravity, which attributed the force to the unseen warpage of four-dimensional space-time.

LIFE-CHANGING NEWS

Christmas 1962 was a pivotal moment in Hawking's life. In his final year at Oxford, he had noticed that he was becoming unaccountably clumsy and, when he returned home at the end of his first term at Cambridge, his mother persuaded him to see a doctor. Exhaustive tests during a two-week stay in hospital led, in early 1963, to the diagnosis of motor neurone disease, a progressive deterioration of the brain cells that

Hawking claimed to have only done around 1,000 hours' work during his three years at the University of Oxford, but his ALS diagnosis spurred him on to work harder in the subsequent years

GETTY, SWNS.COM

> "Aged just 21, Hawking faced a death sentence. But although he must have suffered bouts of depression, he did not succumb to total despair"

are responsible for movement. Although a person at first loses control over their voluntary muscles, eventually they also lose control of involuntary muscles that control essential reflexes, which leads to death. The disease normally runs its course within two years.

Aged just 21, Hawking faced a death sentence. The extraordinary thing is that, although he must have suffered bouts of depression, he did not succumb to total despair. In part, this was thanks to Jane Wilde, who he fell in love with after meeting her at a student party. The pair married in 1965. Bolstered by her unflagging support, Hawking decided to make the most of his short life expectancy. The time limit on his life focused the mind of the formerly lazy student and, for the first time, his PhD work began to flow. Even more miraculously, towards the end of the second year of his research, the progression of his disease began to slow. Amazingly, it seemed he might have more than two years left to him.

MAKING WAVES

Hawking's first important work was carried out with Roger Penrose of the University of Oxford. Between 1965 and 1970, the pair proved a number of powerful theorems, which showed that, according to Einstein's theory of gravity, the Big Bang in which the Universe was born 13.82 billion years ago must have been a singularity [see 'Singularities', p50]. Since a singularity is a point at which all physical quantities sky-rocket to infinity – an impossibility – it signals that a theory has broken down. In order to understand

GETTY, EMILIO SEGRÈ VISUAL ARCHIVES/AIP

ABOVE: At the Institute of Theoretical Astronomy at the University of Cambridge, 1970. Hawking is on the far left of the bottom row. To Hawking's left sit astronomers Virginia Trimble and Martin Rees (now Astronomer Royal), two seats to the right of Fred Hoyle

LEFT: Hawking at the University of Cambridge in 1990, two years after *A Brief History of Time* had made him famous

the birth of the Universe, a better theory than Einstein's is therefore needed. Many think this is a quantum theory of gravity, which has so far proved elusive despite the best efforts of physicists.

For his next trick, in 1974 Hawking stunned the world by showing that black holes are not totally black. Despite not possessing a quantum theory of gravity, Hawking was able to apply quantum theory – the description of the microscopic world of atoms and their constituents – to the event horizon that surrounds a black hole and marks the point of no-return for in-falling light and matter. He showed that quantum processes cause the horizon to glow with emitted subatomic particles, which became known as Hawking radiation [See 'Black holes', p54].

Hawking's third major contribution to physics, in the early 1980s, was the no-boundary condition universe [See 'The no-boundary Universe', p66]. Working with American physicist James Hartle, now of the University of California in Santa Barbara, he tried to write down a quantum wave function (a mathematical equation) that describes the entire Universe. Hawking and Hartle realised that Einstein's theory of gravity can be reformulated so that, instead of having three dimensions of space and one of time, it has three dimensions of space and one of imaginary time, a mathematical concept that – crucially – behaves just like space. It means that the wave function of the Universe, which today exists in space and time, could have started out in space alone. It would neatly remove the awkward question, 'what happened before the Big Bang?', which would be as meaningless as asking, 'what is north of the North Pole?'

THE BOOK THAT CHANGED EVERYTHING

Hawking's work with Hartle coincided with an extraordinary development in his life – one which did not concern scientific research directly. In 1982, he'd begun writing a popular science book that was published in 1988 as *A Brief History of Time*. A publishing phenomenon, by May 1995, it had been on *The Sunday Times*'s bestseller list for a record 237 weeks, a feat that earned it an entry in the 1998 *Guinness Book of Records*.

Hawking, like Princess Diana, was catapulted into the mega-league of global stardom, previously the preserve of Chaplin and Einstein. He became the best-known and most recognisable scientist on the planet. Almost certainly the public's

imagination was caught, to a significant extent, by the apparent contrast between the man paralysed in a wheelchair and the man whose mind wrestled with the biggest mysteries of the Universe – everything from the nature of black holes and the possibility of time travel to the origin of the Universe. From 1979, Hawking was the Lucasian Professor at of Mathematics at the University of Cambridge, a Chair previously occupied by Isaac Newton and Charles Babbage.

What also impressed the public about Hawking was his tremendous courage and determination in the face of adversity. He was the longest surviving person with motor neurone disease in the UK, but he lived as normal a life as was possible. He had three children. After divorcing Wilde, in 1995 he got married again to his nurse, Elaine Mason, then divorced again. In 2007, he even flew on the Vomit Comet, a converted passenger jet that simulates weightlessness. It was incredibly moving to see the smile on his face as he left the constraint of his wheelchair for the first time in decades.

Hawking lost his voice after an emergency tracheotomy in the summer of 1985. However, his computerised voice system – which had been installed for him by Mason's ex-husband – became instantly recognisable across the world.

A LIFE LESS ORDINARY

Hawking revelled in the opportunities his fame provided. In 1993, he appeared in *Star Trek: The Next Generation* as a hologram of himself, playing poker with holograms of Sir Isaac Newton and Albert Einstein (making Hawking the only person ever to play himself on the show). He appeared in *The Simpsons* on 29 October 1995, with Homer Simpson saying: "There's so much I don't know about astrophysics. I wish I read that book by that wheelchair guy." More recently, in 2012, he made his first guest appearance on *The Big Bang Theory*, pointing out an error in Sheldon's thesis, and in 2014 he appeared with Brian Cox in a Monty Python sketch.

Hawking's sense of humour played a key role in keeping him cheerful. In 2015, he teamed up with David Walliams for a Comic Relief sketch in which he played Matt Lucas's wheelchair-bound character Andy. He even uttered Andy's catchphrases "Yeah, I know" and "Don't like it" in his distinctive voice before telling Walliams, playing Andy's carer Lou, to "P*** off!"

"Hawking's positive attitude epitomised the triumph of the human spirit over seemingly insurmountable obstacles"

Hawking's positive attitude to life epitomised the triumph of the human spirit over seemingly insurmountable obstacles. "The only bad luck I've had is motor neurone disease," said Hawking at the Royal Institution in 2017. "In everything else I've been lucky." He said this even as his disease progressed inexorably. Fewer and fewer muscles were now available to control the cursor by which he selected words on his speech synthesiser. A few years ago, he was relying on a single twitching cheek muscle. Knowing that this muscle, too, would eventually fail, he

OPPOSITE: Hawking's PhD thesis, which he completed in October 1965

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ESSENTIAL VIEWING

HAWKING ON THE SILVER SCREEN

A brief history of Hawking biopics

The 2014 film *The Theory of Everything*, which starred Eddie Redmayne as Hawking (pictured right), was a huge commercial and critical success, picking up five Oscar and 10 BAFTA nominations, and winning one and three of them respectively. The film was based on Jane Hawking's 2007 memoir *Travelling to Infinity: My Life with Stephen*, which was itself an updated edition of her 1999 book *Music to Move the Stars*. The latter was written while the couple were estranged, and Jane rewrote it once they became reconciled (after Hawking's second marriage broke down).

But the film wasn't the first to depict Hawking's life in film: that honour goes to the 1991 Steven Spielberg-produced film version of *A Brief History of Time*, which was really much less about the book than it was about its author.

ACKNOWLEDGEMENTS

I wish to thank my supervisor, Dr. D. W. Sciama for his help and advice during my period of research.

I would also like to thank Mr. B. Carter and Dr. G. F. R. Ellis for many useful discussions. I am indebted to R. G. McLenaghan for the calculation of the Bianchi Identities in Chapter 3.

The research described in this thesis was carried on while I held a Research Studentship from the D.S.I.R.

S. W. Hawking

15th October 1965 S. W. Hawking

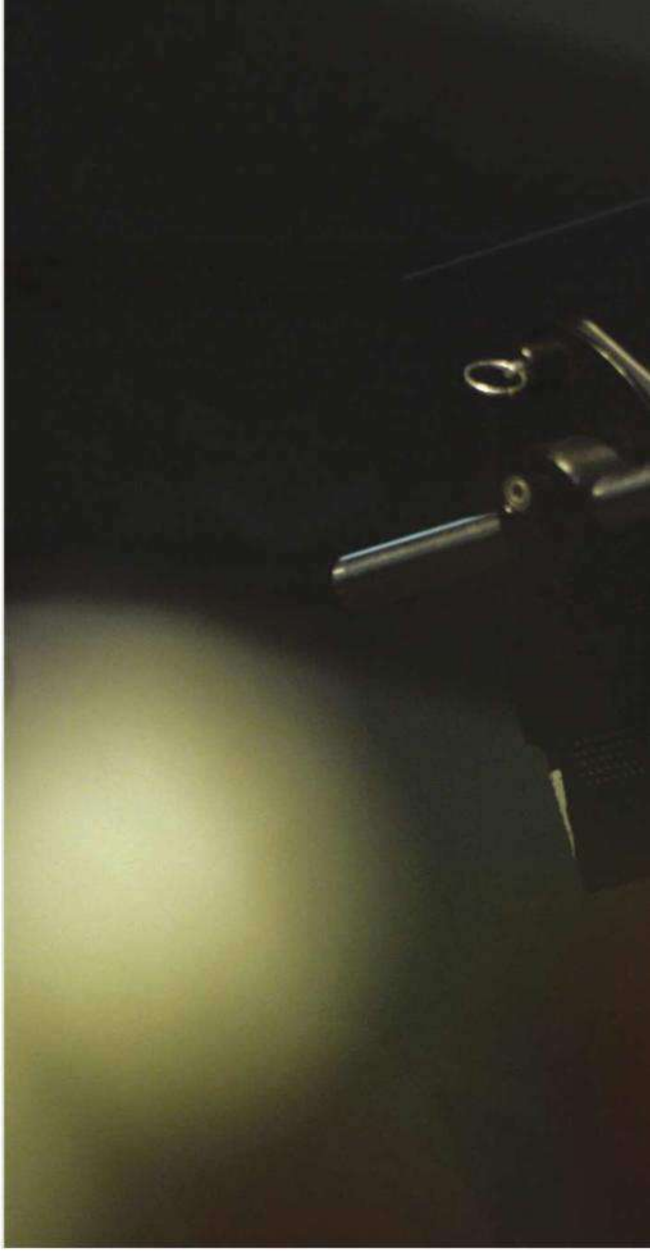
This dissertation is my original work

S. W. Hawking

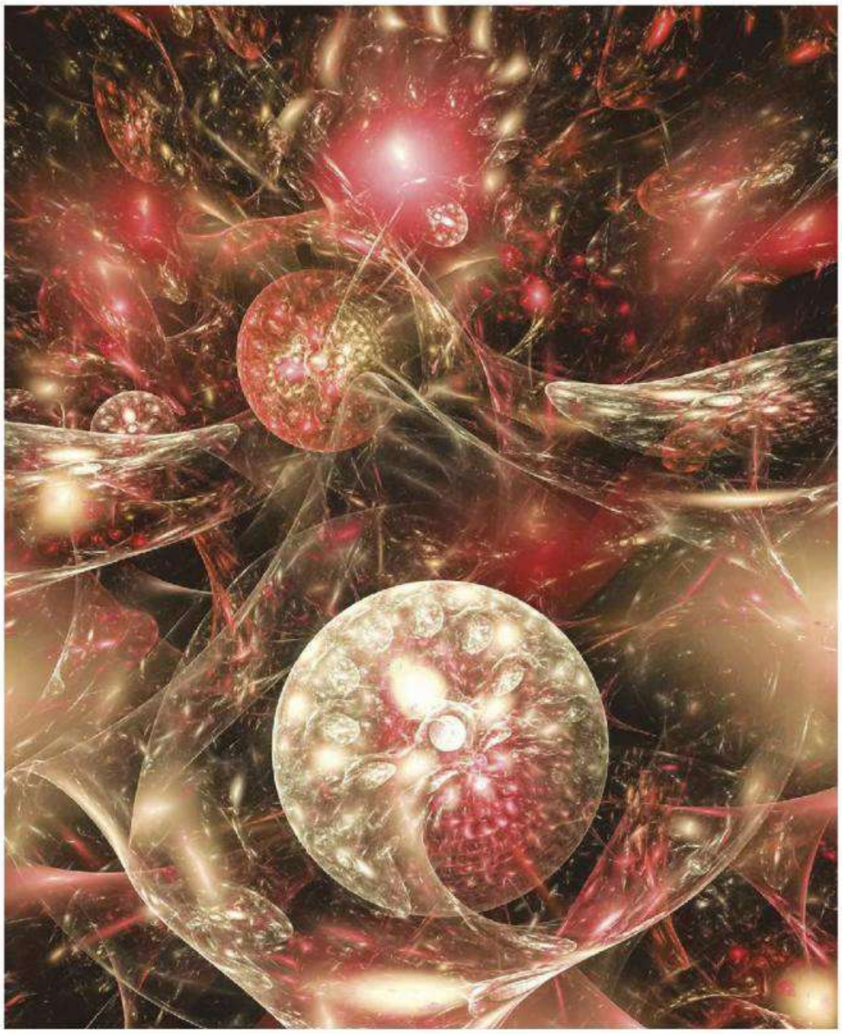
trialled a device that could read his mind via the brain waves it generated.

Hawking displayed incredible energy, which often exhausted his colleagues. I remember, as a graduate student at the California Institute of Technology in Pasadena, swimming in an outdoor pool when I looked up and was astonished to see Hawking in his wheelchair. His young son and a friend were splashing about in the shallow end. Even back then – and this was 1983 – I had thought Hawking too ill to travel. How wrong I was: Hawking kept up a punishing schedule of work and travel until well into his seventies.

Not surprisingly, Hawking – who will surely be remembered as one of the great global figures of the past century – was often the subject of veneration. "I had the privilege of having dinner with Stephen Hawking three times, but I never spoke to him (too awed)," says physicist and science writer Graham Farmelo. "But I did once interact with him, at a Rutherford Lab meeting in the 1970s, when I accidentally pushed a button on his wheelchair that instantly ejected him!"



BELOW: Hawking's last pieces of research centred on the possibility that rather than one Universe, we may live in a multiverse containing millions of universes, as visualised below



In the last year before he died, Hawking was working with Thomas Hertog of the University of Leuven in Belgium on inflation in a no-boundary universe. Inflation is the period of super-fast expansion of the vacuum that is thought to have preceded the Big Bang, and which unavoidably creates a vast multiverse of parallel universes. Hawking and Hertog were able to demonstrate that the multiverse might actually be a lot smaller than people suspected – and, most importantly, that it should be scientifically testable, which many had feared it might not be [See 'Hawking's final predictions, p70].

FIGHTING FOR THE NHS

Recently, however, physics was not Hawking's only concern. The welfare of Britain's National Health Service occupied much of his time.

"The NHS has lost a great friend and champion," says Dr Louise Irvine, a doctor and campaigner against cuts to the National Health Service, on hearing of Hawking's death. Hawking, who credited the NHS treatment he received for making

GETTY, ALAMY

his long life with ALS possible, passionately opposed privatisation.

"The NHS must be preserved from commercial interests who want to privatise it," he said in 2012. "I would have died but for the NHS hospital care. We must retain this critical public service, and prevent the establishment of a two-tier system."

At a meeting at the Royal Society of Medicine on 19 August 2017, Hawking spoke passionately about the NHS, criticising the UK government's treatment of the service, the threat of privatisation and the abuse of statistics by the Secretary of State for Health, Jeremy Hunt. He entered into a debate with Hunt and many doctors wrote to *The Guardian* in support of what Hawking said.

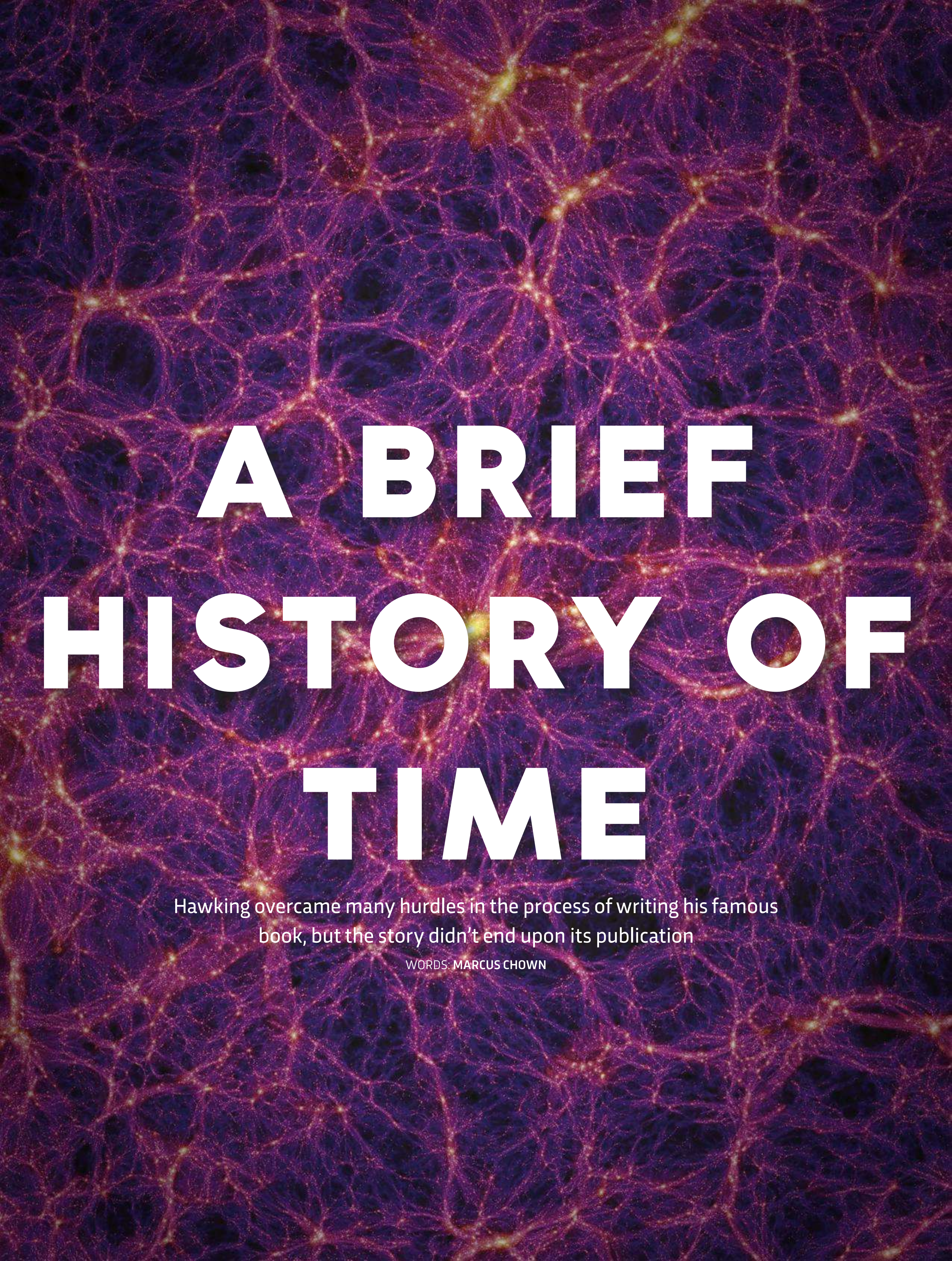
In the past year, Hawking and the other four claimants in the JR4NHS judicial review challenged the government's plans to impose US-style 'accountable care organisations' on the NHS. His participation in the review gave it a huge boost in terms of public awareness and credibility (a headline in *The Independent* on 29 January 2018, for instance, read: "Stephen Hawking and leading doctors to take Jeremy Hunt to court").

ONE LAST HURRAH?

In fighting for social issues, pushing back the boundaries of physics and his sheer enjoyment of living, there is no doubt Hawking lived a full and rich life. The one top-ranking honour that he didn't receive during his extraordinary lifetime was the Nobel Prize for Physics. In large part, that's because the Nobel committee likes to see supporting observational or experimental evidence of theories – and although black holes litter the Universe, with every galaxy including our own harbouring a supermassive version in its heart, no one has ever seen Hawking radiation.

Nevertheless, people are building black hole analogues in laboratories around the world, creating uncrossable boundaries that mimic a black hole horizon. With such research going on, it is only a matter of time before Hawking radiation is seen on Earth. A case, if ever there was one, for a posthumous Nobel Prize?

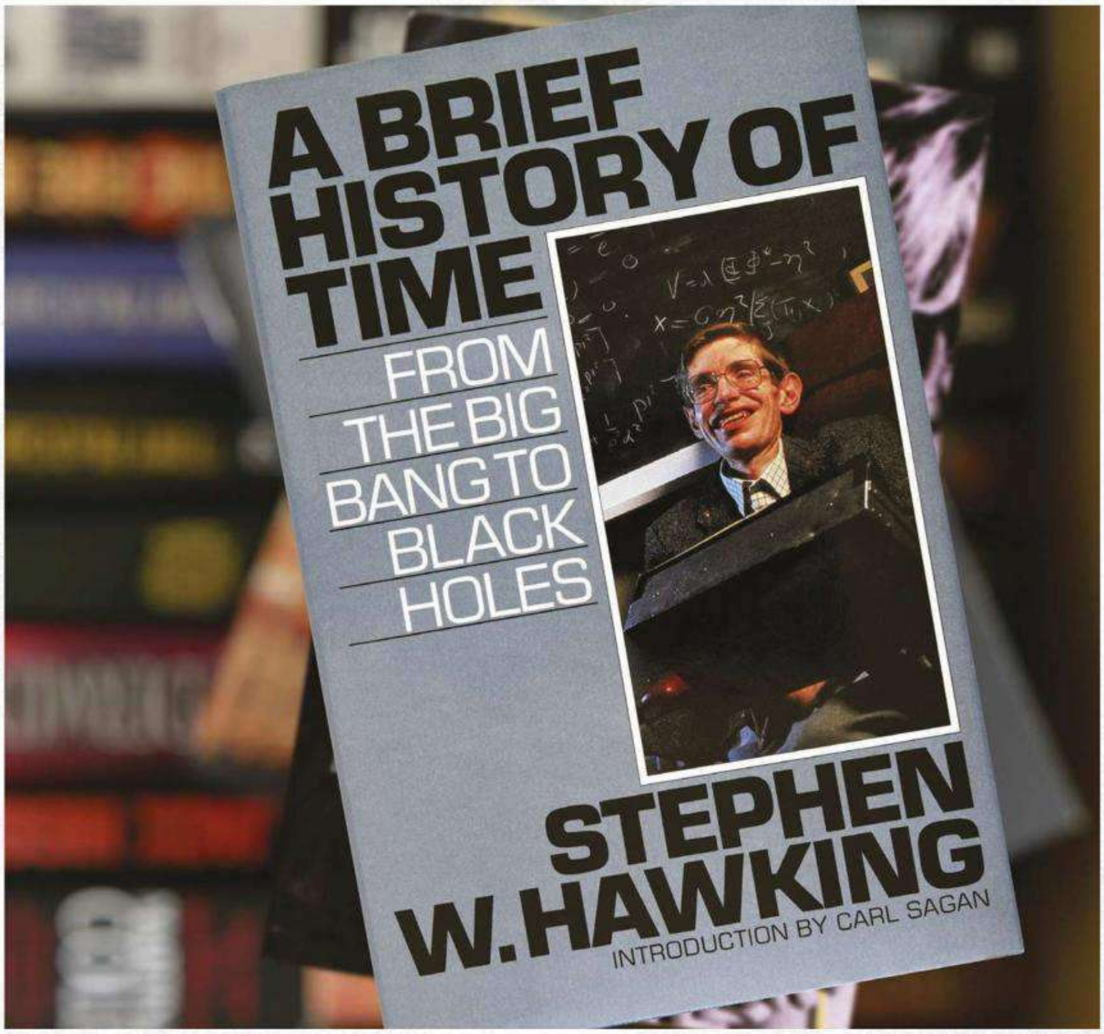
ABOVE: Hawking gives a lecture at the Hebrew University of Jerusalem, 2006



A BRIEF HISTORY OF TIME

Hawking overcame many hurdles in the process of writing his famous book, but the story didn't end upon its publication

WORDS: **MARCUS CHOWN**



CLOCKWISE FROM ABOVE: After years of revisions, the book Stephen Hawking began in 1982 was finally published in 1988; debris from Pan Am Flight 103, which was destroyed over Lockerbie; Kylie Minogue celebrates the success of her single *I Should be so Lucky*; the deaths of 167 people made the Piper Alpha disaster the world's most deadly oil platform fire

SCIENCE PHOTO LIBRARY, GETTY X2, ALAMY X2

It was 1988. Ex-soap star Kylie Minogue topped the charts with *I Should be so Lucky*. In the North Sea, 167 people died in the inferno that destroyed the Piper Alpha oil rig and, above Lockerbie in Scotland, a bomb detonated on board Pan Am Flight 103. The late-September launch of mission STS-26 aboard the space shuttle Discovery was the first lift-off for NASA's vehicle since Challenger disintegrated 71 seconds into its flight in 1986. But the most significant event in the world of science was, arguably, not a scientific discovery but the publication of a book: *A Brief History of Time*.

It all began in 1982 when Stephen Hawking, famous for his work on the theory of black holes and for being cruelly confined to a wheelchair by motor neurone disease, became dissatisfied with the popular books on his specialist subject and decided to have a go himself. *A Brief History of Time* had a long gestation. When Hawking delivered his draft, the editor at his publisher, Bantam, came back to him with lots requests for clarification. Initially irritated by this, Hawking eventually realised that the editor was right. In fact, the feedback also confirmed what someone else told him: every equation in the book will halve its readership (in the end, Hawking kept just one: $E=mc^2$).

But the biggest hurdle Hawking had to overcome in completing an extensive revision of his book was a medical one. In the summer of 1985, while in Geneva, he came down with pneumonia. He couldn't breathe and his life was saved by an emergency tracheotomy. But the procedure cut the nerves to his vocal chords. His voice had been deteriorating for many years and, whenever he gave scientific talks, a graduate student interpreted for him. But now there was no way back. His voice had gone forever.

Hawking was given a computerised voice, using a piece of software called Equalizer and a hardware speech synthesizer from Speech

Plus, running on a portable computer that was attached to his wheelchair by David Mason, ex-husband of the nurse Hawking would later marry, then divorce. It was this voice that became synonymous with Stephen Hawking, and which he stubbornly held onto despite technological advances that might have improved it.

Despite all the setbacks, Hawking finished his revisions of *A Brief History of Time* and the book was published. It contained an introduction by Carl Sagan, front man of the *Cosmos* TV series and, at the time, one of the most successful science popularisers in the world. The book was published on 1 April 1988. If anyone thought the date an inauspicious one, they would be proved spectacularly wrong by the phenomenal success of the book. It spent a record 237 weeks on *The Sunday Times's* bestseller list and earned a place in the 1998 *Guinness Book of Records*. It has now sold well in excess of 10 million copies in dozens of languages.

To this day, nobody can really say just why the book has been so successful – if publishers knew, they'd have repeated the success with other books. Perhaps it was the inspired and evocative title. Perhaps it was the author himself: a brilliant mind trapped inside a malfunctioning body but still able to range freely over the length and breadth of the cosmos. Or perhaps it was the mind-blowing subject matter.

"It spent a record 237 weeks on *The Sunday Times*'s bestseller list and earned a place in the 1988 *Guinness Book of Records*"

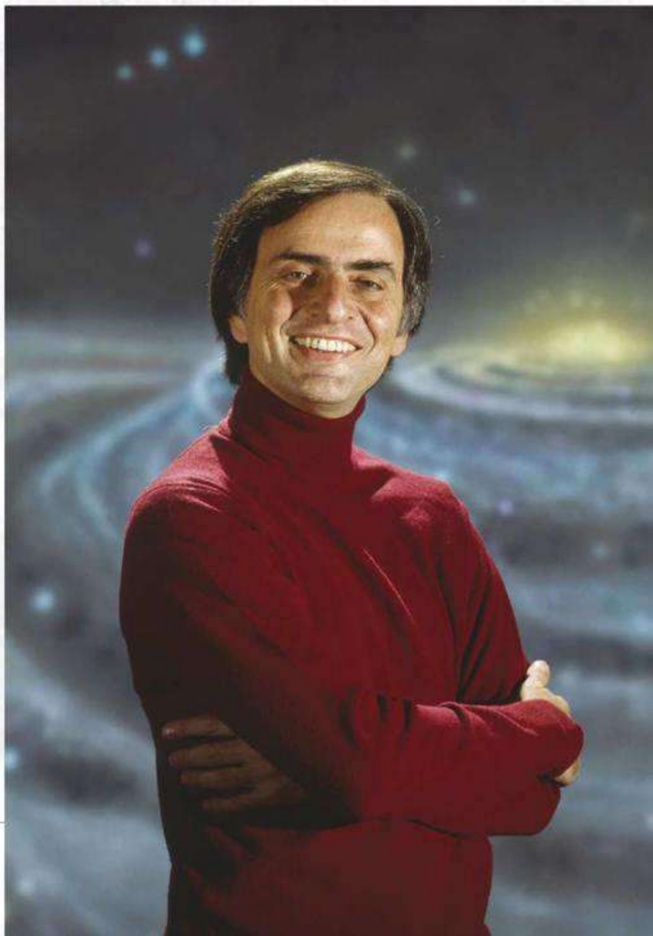
"Where did the Universe come from?" wrote Hawking in the Foreword. "How and why did it begin? Will it come to an end and, if so, how?" These are the biggest questions in science. Formerly, they had been the preserve of religion. But, in 1988, it was possible for physicists to ask those questions – and have a fighting chance of finding the answers within a generation.

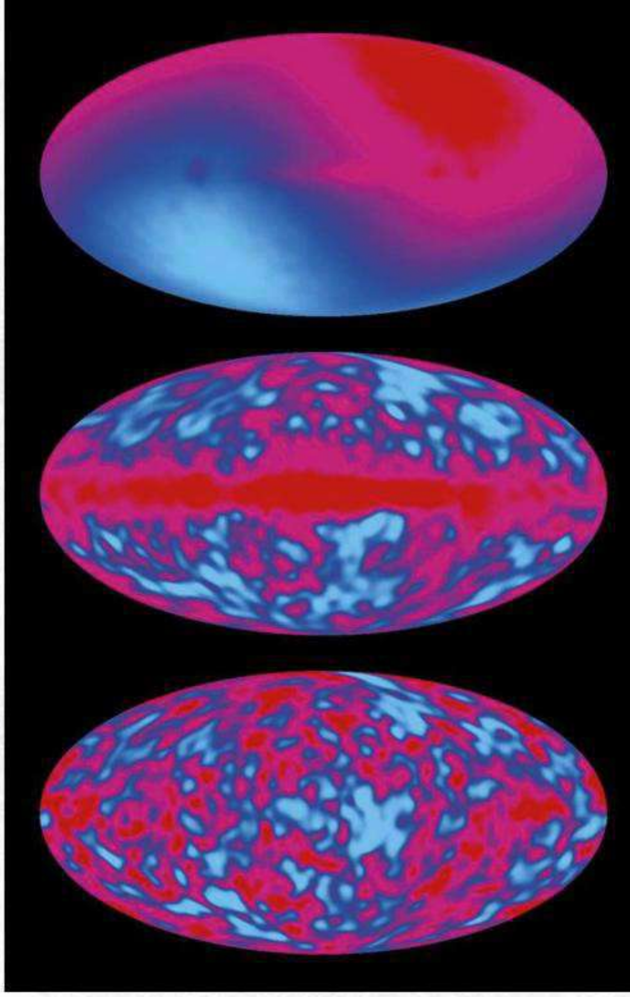
GETTING TO BIG FROM A SMALL BEGINNING

The theory of big things – stars, galaxies and the Universe – is Einstein's theory of gravity; the theory of small things – atoms and their constituents – is quantum theory. Both are phenomenally successful in their own domains. However, in its earliest moments, the Universe

BELOW: From his office in the University of Cambridge. Hawking was able to communicate his understanding of the Universe to the world

BELOW RIGHT: The American scientist Carl Sagan, who found fame as the writer and presenter of the landmark TV series *Cosmos*, wrote the introduction to Hawking's *A Brief History of Time*





ABOVE LEFT: NASA launched the Cosmic Background Explorer (COBE) to measure the residual infrared and microwave radiation from the Big Bang

ABOVE: Data collected by COBE was used to produce images of the remnants of Big Bang, essentially first ever 'baby pictures' of the Universe

– a big thing – was smaller than an atom. Understanding the birth of the Universe and addressing Hawking's big questions therefore required finding a deeper theory of physics – a theory of everything – that somehow united Einstein's theory of gravity (the General Theory of Relativity) with quantum theory.

In *A Brief History of Time*, Hawking described Einstein's theory, in which gravity is nothing more than the warping of space-time by matter, and he also described quantum theory, which explains pretty much every aspect of the everyday world to a phenomenal degree of accuracy. At the end of his book, he also introduced string theory, a highly speculative framework that might, plausibly, be a step on the road to the elusive theory of everything. Certainly, string theory, which views the fundamental building blocks of the world as ultra-tiny strings of mass-energy vibrating in 10-dimensions of space-time, is the only framework so far discovered that's compatible with both relativity and quantum theory.

Since the publication of *A Brief History of Time*, an enormous amount has changed. Perhaps the biggest development has been the transformation of cosmology – the science that deals with the origin, evolution and fate of the Universe – from a largely theoretical science into a precision field of study, supported by reliable data. In 1989, NASA's Cosmic Background Explorer (COBE) carried instruments to study the afterglow of the Big Bang fireball, the oldest fossil in creation, which carries an imprint of the Universe when it was just 380,000 years old. Most famously, it found subtle variations in the temperature across the sky. Such cosmic ripples were the long-sought 'seeds' of giant superclusters of galaxies in today's Universe. They were the missing jigsaw piece in cosmic history, revealing how the transition was made from the smoothness of the fireball to the lumpiness of today's galaxy-strewn universe.

COBE and its successor, the Wilkinson Microwave Anisotropy Probe (WMAP), heralded a golden age of cosmology. But whereas observations of the afterglow of creation largely confirmed the predictions of the Big Bang model, another discovery was tantamount to a bombshell dropped into the very heart of cosmology. Dark energy, discovered in 1998, is invisible, fills all of space and its repulsive gravity is speeding up the Universe's expansion. But nobody knows what it is. In fact, our best theory of physics – quantum theory – overestimates its energy by 1 followed by 120 zeroes. This is the biggest discrepancy between an observation and a prediction in the history of science. Something, somewhere in our understanding of the Universe, is badly wrong.

Ironically, just before the discovery of dark energy, Hawking had claimed that physicists were close to finding the theory of everything, which distils all physical phenomena into a

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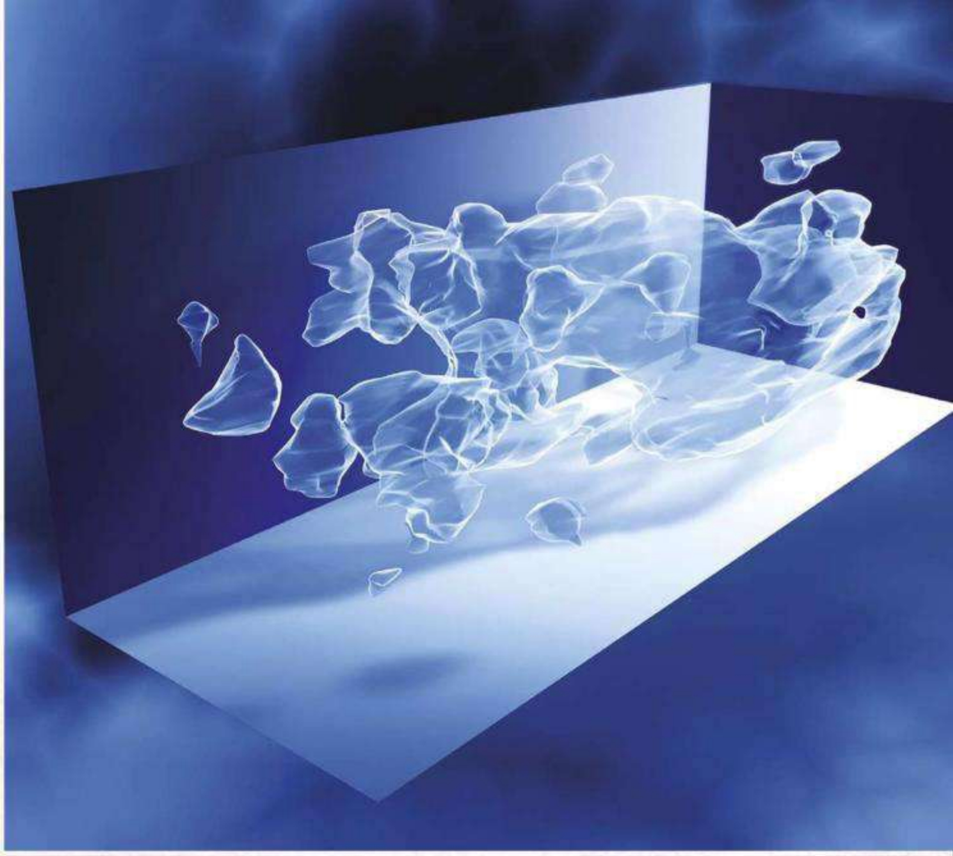


ABOVE: The world's gravitational wave detectors came online just in time to pick up the ripples produced by the merger of two black holes that occurred 1.3 billion years ago

ABOVE RIGHT: A 3D map showing the distribution of dark matter running through a section of the Universe

OPPOSITE: Hawking at work at the University of Cambridge in the late 1970s. His motor neurone disease had already robbed him of his ability to walk but had yet to take his speech

neat set of equations. By joining a long line of physicists who have got egg on their faces by making similar predictions, he proved he was not infallible. Dark energy accounts for 68.3 per cent of the Universe's total mass-energy. Incredibly, until 20 years ago, we had overlooked the biggest mass component of the Universe!

DASHED HOPES

The quest for a theory of everything has proved harder than Hawking anticipated. The reason for his enthusiasm in *A Brief History of Time* was that, in 1984, Michael Green of Queen Mary College in London and John Schwarz of the California Institute of Technology in Pasadena had shown for the first time that string theory could give sensible predictions. Hawking and many others hoped that it would pin down the masses and strengths of nature's fundamental particles and forces. Unfortunately, in recent years, that hope has evaporated with the discovery by theorists that there are at least 10,500 string theories, each with different particles and forces.

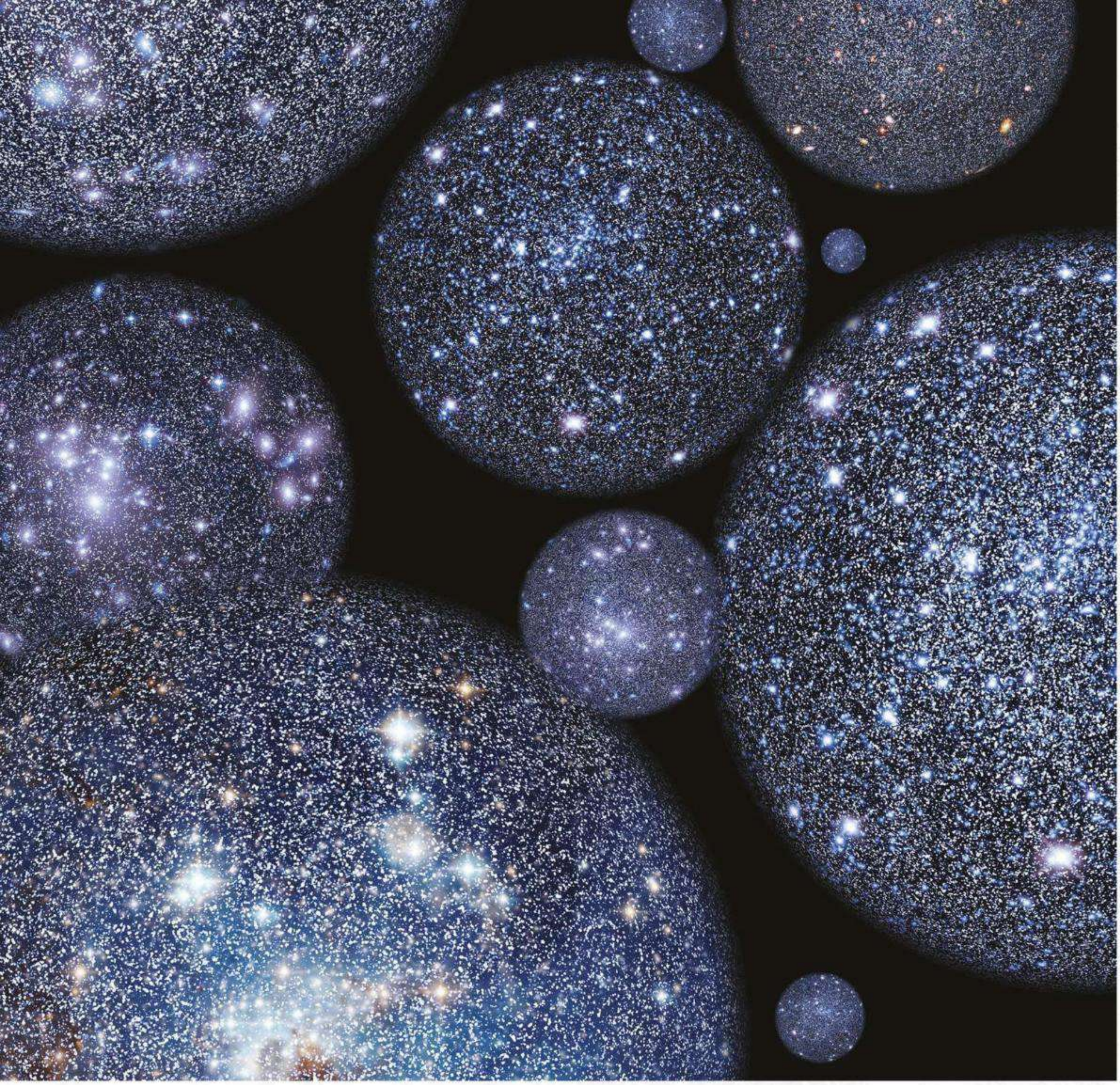
At least this so-called string landscape provides a possible location for the 'multiverse', a vast ensemble of parallel universes that has been increasingly favoured by physicists since 1988. Though some physicists abhor the idea of domains of space-time forever beyond direct observation, others accept that there is evidence from several different directions that our Universe is not the only one.

Other things that have become important since 1988 include gamma-ray bursters, now known to be explosions as much as a million times as energetic a normal supernova, and dark matter. Though already known about in 1988, dark matter has now assumed a central place in Big Bang models, alongside dark energy. Nobody knows what dark matter is – it could be as-yet-undiscovered subatomic particles, or possibly fridge-sized black holes with the mass of Jupiter. But it outweighs visible stars and galaxies by a factor of about six. If you know what dark matter is, there's a Nobel Prize waiting for you in Stockholm.

"By joining a long line of physicists who have got egg on their faces by making similar predictions, Hawking proved he was not infallible"

There's no doubt, however, that black hole science has blossomed since the publication of *A Brief History of Time*. In 1988, only about 10 good candidates were known in our Milky Way; now it is closer to 100. More significantly, in the 1990s, NASA's Hubble Space Telescope discovered that essentially every galaxy appears

NASA/ESA/R MASSEY, SCIENCE PHOTO LIBRARY, IAN BERRY/MAGNUM PHOTOS



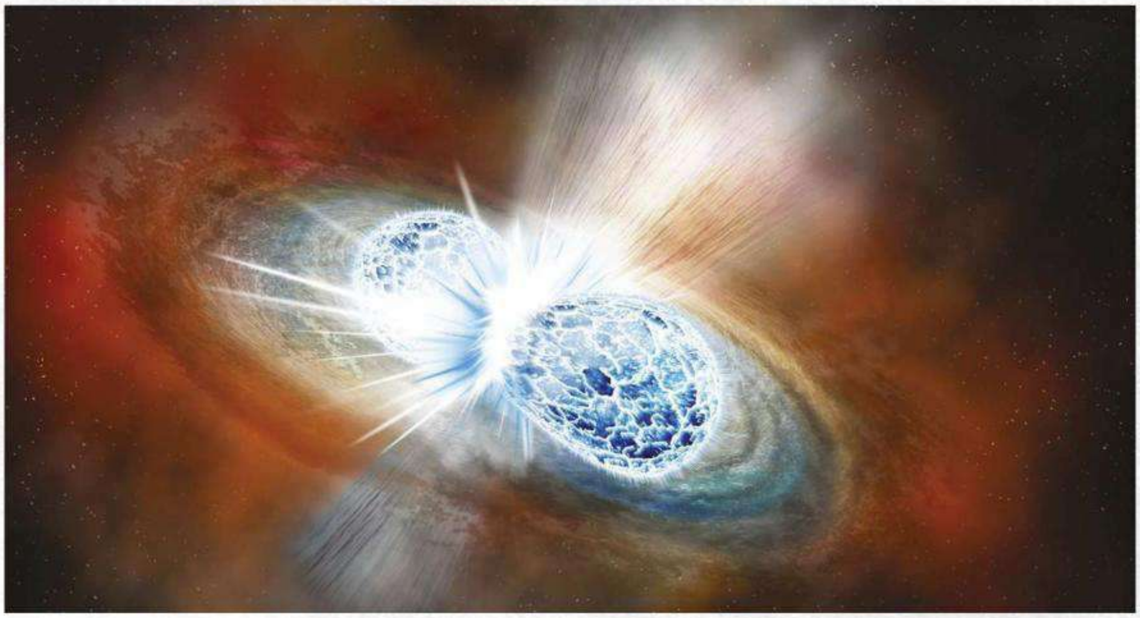
GETTY, ROBIN DANIEL/CARNEGIE INSTITUTION FOR SCIENCE, IAN BERRY/MAGNUM PHOTOS

ABOVE: Advances in string theory suggest the existence of a multiverse may be possible, but scuppered Hawking's hopes of finding a theory of everything

to harbour in its heart a monstrous supermassive black hole. Nevertheless, the fact remained that, although the evidence for the existence of black holes was overwhelming, it was indirect: the swirling of matter at great speed around a massive, compact body. But everything changed on 14 September 2015 when gravitational waves – ripples in the fabric of space-time predicted by Einstein almost a century before – were picked up on Earth the first time.

In a distant galaxy, at a time when the most complex organism on Earth was a bacterium, two huge black holes were locked in a death spiral. They whirled around each other, kissed and coalesced. In that moment, they unleashed a tsunami of tortured space-time. Briefly, the power in the gravitational waves surging outwards in all directions was 50 times greater than the power emitted by all the stars in the Universe combined. Or, to put it another way, had the merger generated light rather than gravitational

"Throughout human history we've been able to see the Universe – first with our eyes and, more recently, through telescopes. Now, for the first time we can hear it"



ABOVE: Hawking continued his lectures and research at the University of Cambridge while working on the early drafts of *A Brief History of Time*

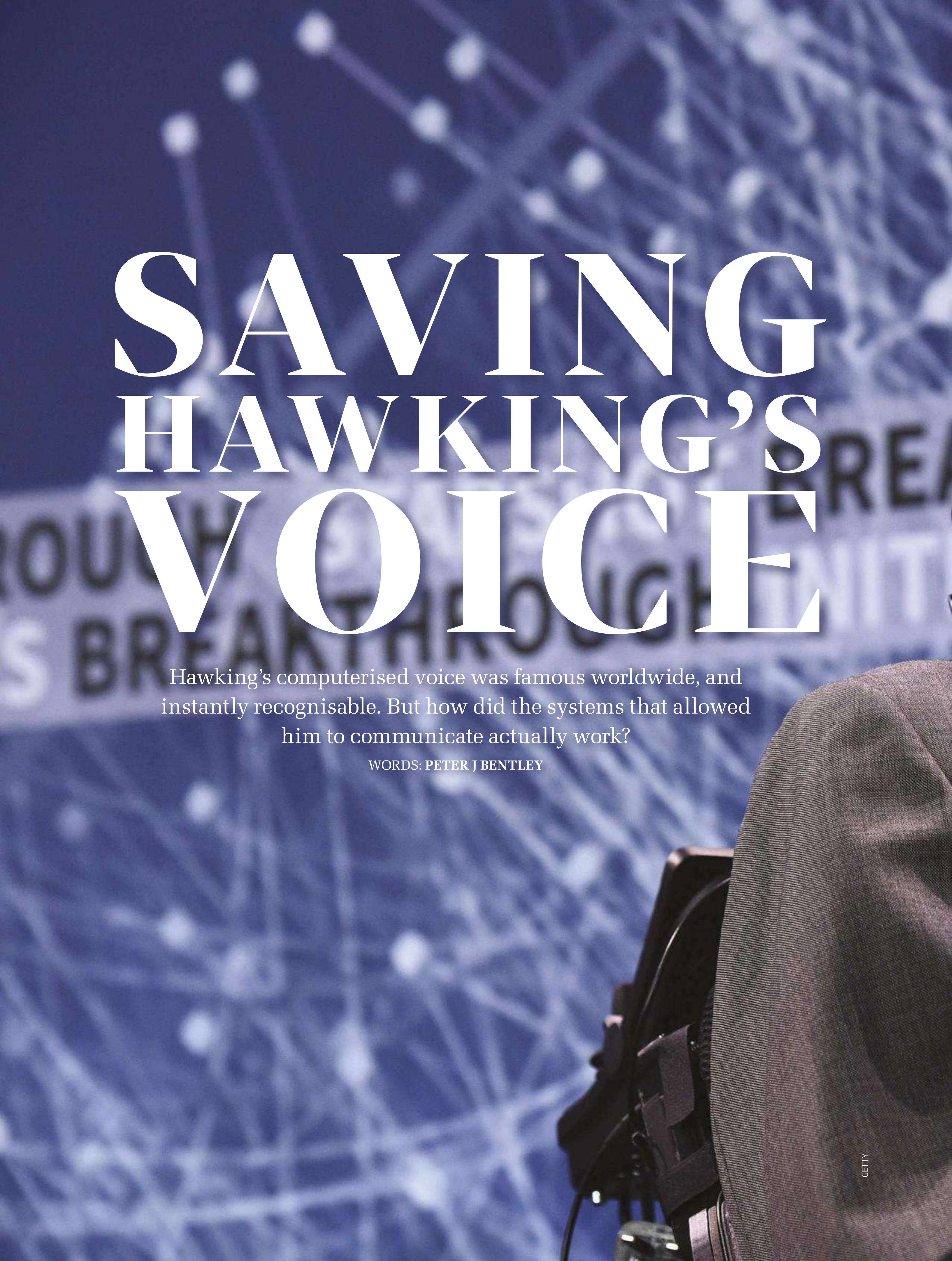
LEFT: Weaker gravitational waves, produced by a collision between neutron stars, were detected for the first time on 17 August 2017

waves, it would have shone 50 times brighter than the entire Universe. It was the single most powerful event ever witnessed by human beings.

The gravitational waves – shrunk to almost infinitesimal size as they rippled across space for 1.3 billion years – displayed exactly the form Einstein's theory predicted for the merger of two black holes. The existence of black holes was, at last, proved beyond doubt.

Since the first merger, four more have been detected – three from black holes and one from super-compact stars known as neutron stars. The significance of these discoveries can't be overestimated. Imagine you've been deaf since birth and suddenly, overnight, you can hear. This is what it's like for physicists and astronomers. Throughout human history we've been able to see the Universe – first with our eyes and, more recently, through telescopes. Now, for the first time, we can hear it. Gravitational waves are the 'voice of space'.

Currently, it's as if we've developed a rudimentary hearing aid, and, at the very edge of audibility, we've caught the rumble of distant thunder. As we continue to improve our gravitational wave detectors, who knows what wonders we'll hear as we tune into the cosmic symphony? These are exciting times for cosmology and the new science of gravitational wave astronomy. And thank goodness Stephen Hawking, master of gravitational physics, was alive to see it born.



SAVING HAWKING'S VOICE

Hawking's computerised voice was famous worldwide, and instantly recognisable. But how did the systems that allowed him to communicate actually work?

WORDS: **PETER J BENTLEY**

GETTY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Stephen Hawking was a pioneer in theoretical physics and cosmology. His scientific advances had given him fame, and he was not afraid to express his opinions widely in all forms of media. Yet despite having such powerful words, for nearly half his life his distinctive voice was generated by a computer.

Hawking was a promising young physicist, but in 1963, at the age of 21, he was diagnosed with a rare, early onset and slow-progressing form of motor neurone disease. The disease causes the death of neurons that control muscles in the body. Hawking decided to use this diagnosis as motivation to achieve his PhD and make significant advances in the understanding of the early Universe, but his body and voice soon became barely controllable. He relied on family members, students and assistants to translate his slurred speech so that he could continue working.

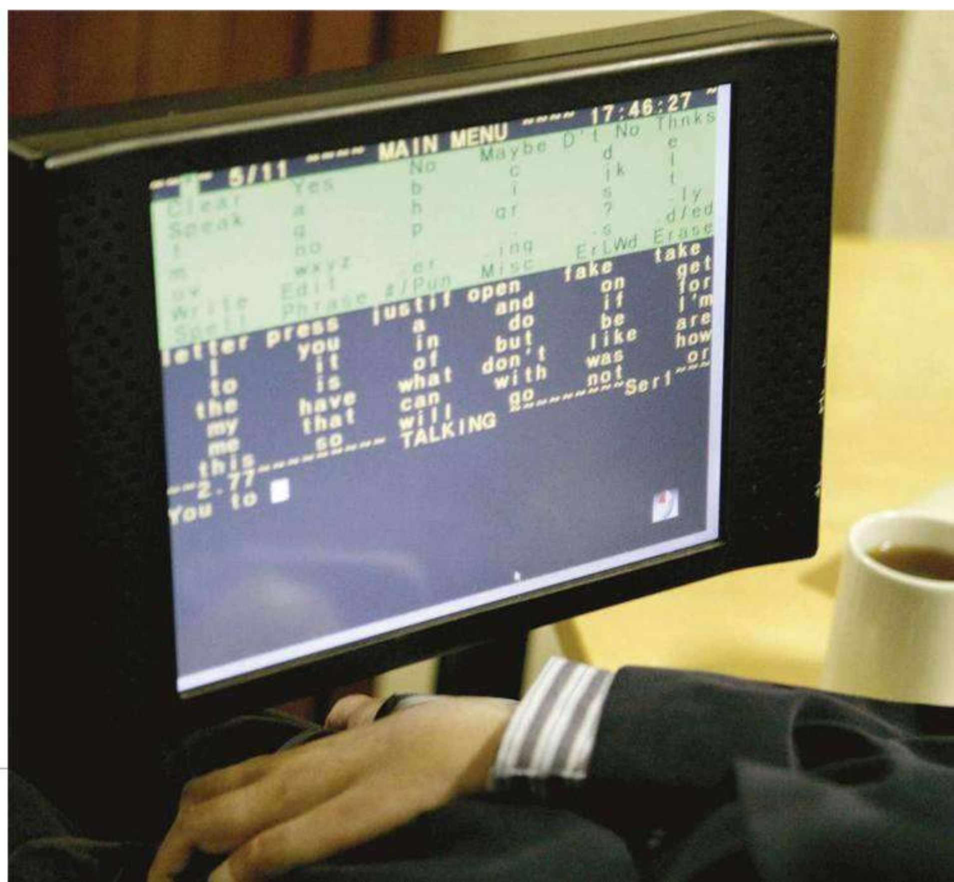
In 1985 everything changed. While on a business trip to CERN, Hawking caught pneumonia and nearly died. His doctors were forced to give him a tracheotomy operation, inserting a tube through his neck to allow him to breath, and irreversibly removing his voice.

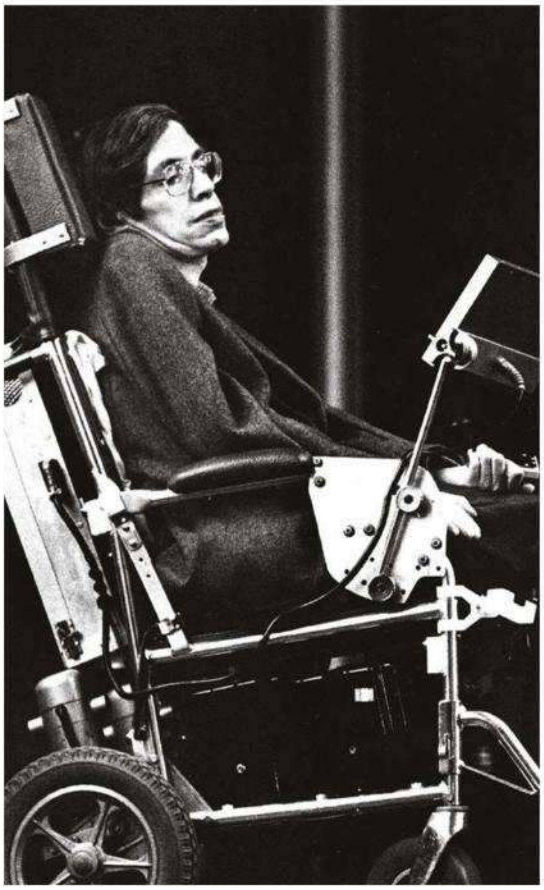
This event led Hawking to think of suicide. His entire career as an academic required him to be able to communicate. He needed to give lectures to his students, to present his scientific findings at conferences, to write scientific papers and books. If he was trapped in a wheelchair with no voice, he could do none of these things. This was, in short, a disaster.

UNDEFEATED

But instead of giving up, Hawking turned to technology. He realised that if he could communicate using spelling cards held up to him, raising his eyebrows to indicate each letter, then a computer might provide a faster solution. Martin King, his doctor, contacted a California-based company called Words+, which seemed to have a solution. The owner had developed the Equalizer for his mother-in-law, who also had motor neurone disease. It was a system operated with a hand clicker that allowed the user to scroll through different words.

"A cursor moves along the upper part of the screen," explained Hawking, "I can stop it by





"I could actually start to speak to him when he got the voice box, and we managed to build up a relationship from then on" Tim Hawking

ABOVE: In his later years, Hawking communicated by means of a single muscle in his cheek, which he twitched to move a cursor on-screen

LEFT: Hawking's communication system was tweaked and upgraded several times over the years

GETTY X2, ALAMY

pressing a switch in my hand. In this way I can select words which are printed on the lower part of the screen. When I have built up a sentence I can send it to a speech synthesizer. I use a separate synthesizer made by Speech Plus, a division of Sentagram Communications Corporation. I can save what I write on disk. I write papers using a formatting program. I can write equations in words and the program translates them into symbols, prints them out on paper in the appropriate type. I can also give lectures. I write the lecture beforehand and save it on disk. I can then send it to the speech synthesizer a sentence at a time. It works quite well, and I can try out a lecture and polish it before I give it. In a similar way, I can make a CD-ROM, but to do this I need a little help from my friends. I get by with a little help from my friends."

Equalizer first ran on an Apple II computer linked to a speech synthesizer made by Speech Plus. The system was made portable and attached to Hawking's wheelchair by David Mason, the engineer husband of one of his nurses. The software was soon upgraded to a new version called EZ Keys made by the same company, which was very advanced for its day. It presented Hawking with an initial screen comprising the alphabet (from which he could choose words starting with that letter), commonly used words, and even tried to predict the next word by showing the following word that Hawking had used the last time he had chosen that word. It provided Hawking with a vocabulary of about 4,000 words.

Hawking could now communicate at 15 words a minute. He made excellent use of the technology: in 1988 Hawking wrote *A Brief History of Time* using the machine. It sold over 10 million copies. The technology was also transformative in a much more personal way: it meant that, at last, he could communicate with his three children, especially his youngest son Tim.

"For the first five or so years of my life," said Timothy Hawking, "I didn't really get to know him as a person, just because I couldn't understand what he was saying. I knew he was my Dad, but I never really bonded with him at all. I could actually start to speak to him when he got the voice box, and we managed to build up a relationship from then on. He'd take me to buy ice creams, and we'd play *Monopoly* together. It's just ironic that it was through the voice of... someone else... that enabled me to build up a relationship with him."

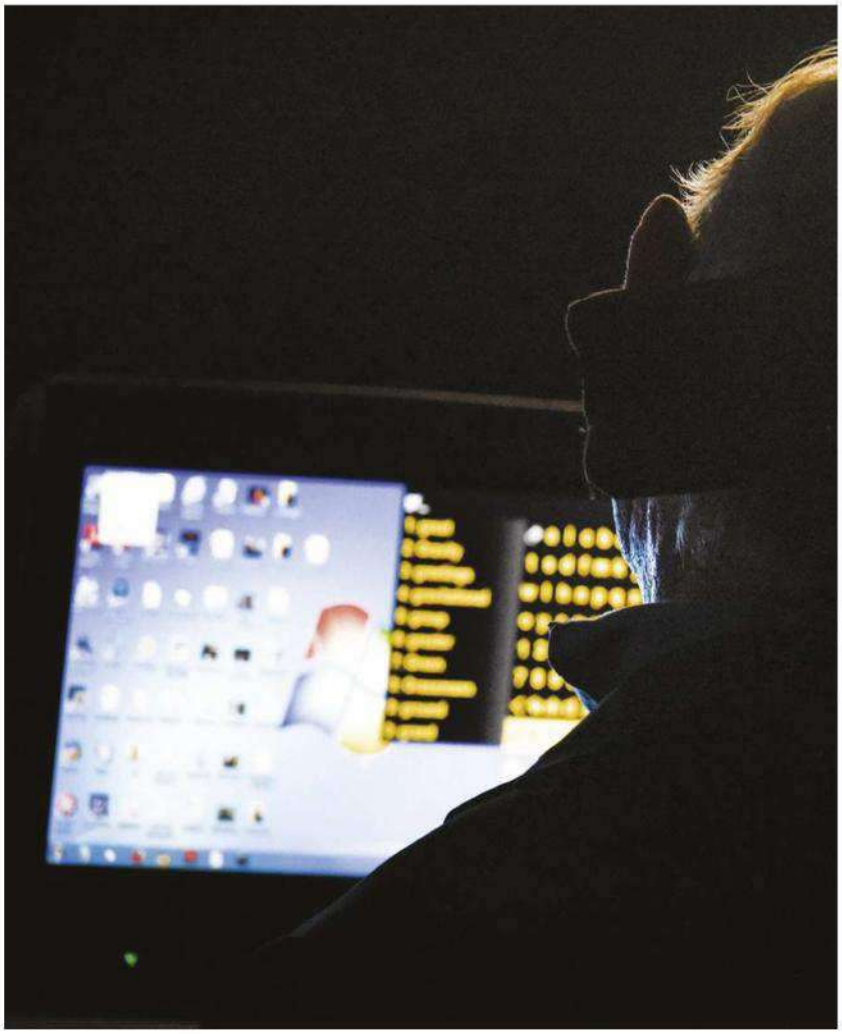
Hawking's disease kept on progressing. By 2005, he no longer had the strength to operate the hand switch, and he asked one of his graduate

BRAIN-COMPUTER INTERFACES

Hawking experimented with devices that let the user control a computer with their mind alone

There are many technologies being developed to enable us to communicate with computers directly from our brains. Some are invasive, such as a cochlea implant, which turns sound into electrical signals that stimulate the cochlear nerve and send audio signals to the brain. Implants to measure signals from the surface of the brain (electrocorticography) provide such good quality readings that some researchers think it may be possible to sense words that people imagine speaking – almost like computer telepathy. Non-invasive methods often use electroencephalogram electrodes placed on the outside of the skull to measure the electrical activity in the brain and turn that into control signals. This approach is now starting to see success for patients who have lost limbs, enabling them to control prosthetic limbs.

But not all brain-computer interfaces are so complex. A recent study showed that a virtual keyboard that pulsates the brightness of each letter at different frequencies, also resulted in the user's pupils pulsating in sync when looking at that letter – enabling users to type by looking, without using electrodes or gaze tracking. All these methods have huge potential to help those with motor neurone disease or other conditions that restrict their ability to communicate or move.



assistants to help. The solution they came up with was an infrared LED and sensor mounted on his glasses that detected the tiny movement of a muscle in his cheek. This was linked to the same software and voice synthesizer that Hawking had been using for decades. Using nothing more than a twitching cheek, Hawking continued his remarkable career, writing several more books.

VOICE HACKING

Hawking's ability to communicate continued to deteriorate as he lost muscle control, and by 2011, he could only manage two or three words a minute. That's when he sent an email to one of the founders of Intel, Gordon Moore, who he had met at a conference in 1997. Moore asked Justin Rattner, Intel's CEO to help.

Rattner put together a team of human-computer interaction experts from Intel Labs, and a few weeks later they met Hawking in his office to discuss how they could assist. After telling him how much they were looking forward to helping him for 20 minutes, they were suddenly stopped by his robotic voice talking. "He welcomed us and expressed how happy he was that we were there," said one of the Intel researchers. "Unbeknown to us, he had been typing all that time. It took him 20 minutes to write a salutation of about 30 words. We now realised that this was going to be a much bigger problem than we thought."

The researchers studied Hawking's current method of communication in depth. They tried

GETTY X2, CASE WESTERN RESERVE UNIVERSITY/CLEVELAND FES CENTER

ABOVE: Hawking announcing the launch of the Breakthrough Starshot initiative at the One World Observatory in New York on 12 April 2016

LEFT: Hawking giving a lecture entitled 'A Brief History Of Mine' at the Starmus Festival in 2016, using the latest version of his voice software

"Hawking was a perfectionist. Despite the hugely laborious interface, he wanted every word spelled perfectly, and every punctuation mark correct"

many new forms of interface. Gaze-tracking seemed like the perfect solution: using video cameras in combination with infrared to detect the position of pupils or corneas, the computer can calculate exactly where the user is looking. With this technology, Hawking could just look at the words he wanted to select. But it didn't work for him – the technology couldn't lock onto his eyes because of his drooping eyelids.

Electroencephalogram (EEG) was another approach. An EEG cap is used to measure brainwaves and select words by thought alone. This way Hawking could communicate even without looking. Unfortunately, this didn't work for Hawking either.

All they had left to try was to improve the input software he used. The researchers soon realised that Hawking was a perfectionist. Despite the hugely laborious interface, he wanted every word spelled perfectly, and every punctuation mark correct. If he missed a letter, he would go back and try to select it, again and again.

With the help of Hawking's graduate assistant Jonathan Wood, the team finally managed to create an improved system. Hawking never got the hang of back buttons, but he benefited greatly from a predictive text system made by Swiftkey that used all of his old documents to figure out the likeliest next word. The system, tailored to Hawking and his specific style, used neural networks (a type of machine learning) to predict the next word – sometimes without Hawking even needing to type a single character. For Stephen Hawking, the most likely first word is 'the', which is usually followed by 'black' and then 'hole'.

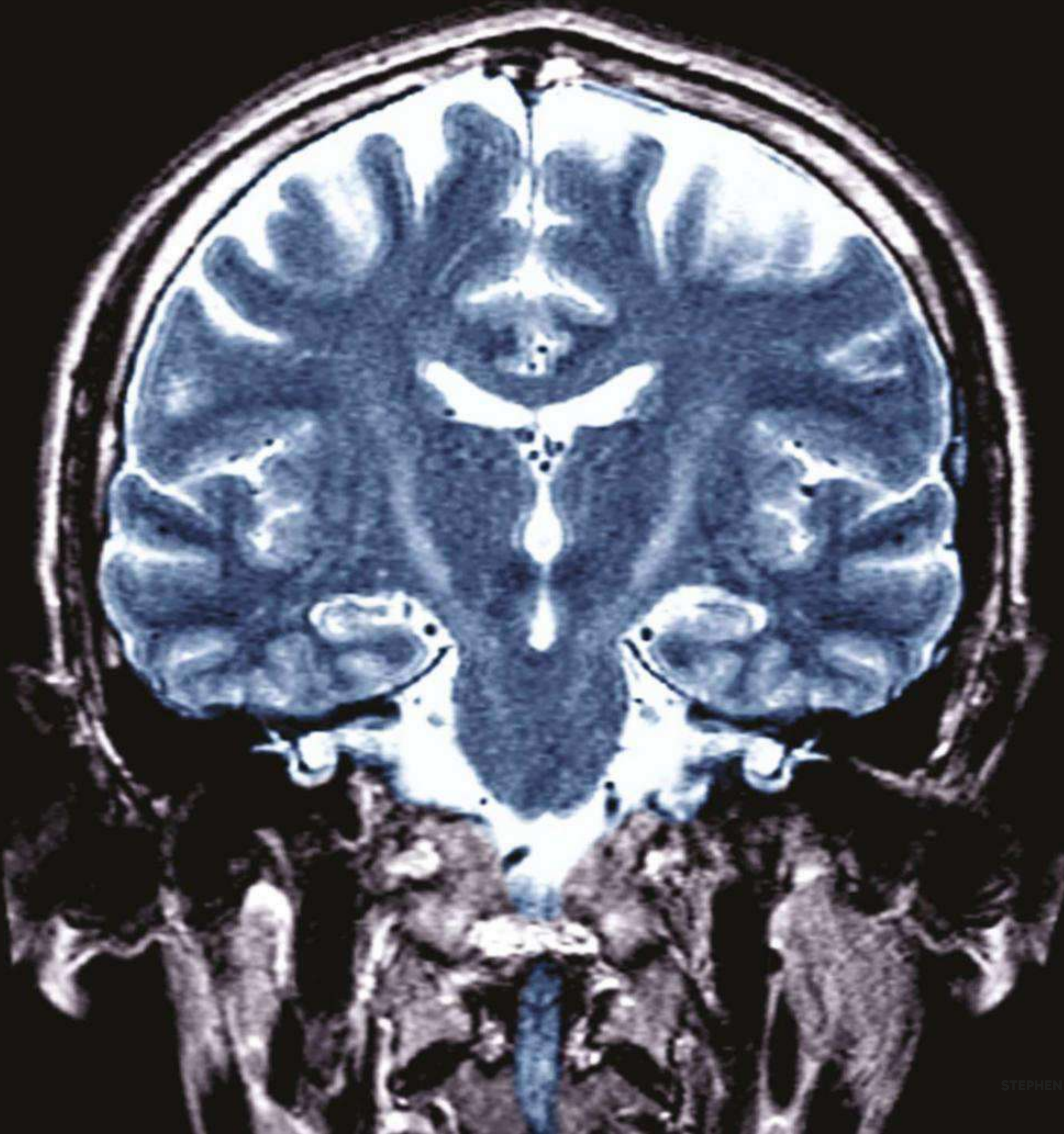
The interface was also improved to provide him with shortcuts to speak, search or email, and give him improved control over the delivery of his lectures. An important addition was a mute option, to stop him from accidentally typing when eating or travelling. Hawking was to use the new system right up until his death in March 2018.

Hawking's voice was famously robotic and artificial. But the innovative hardware and software behind it had given him the freedom to live a truly extraordinary life.

LIFE WITH ALS
HOW HAWKING DEFIED HIS DIAGNOSIS

The disease that confined Stephen Hawking to a wheelchair and took his ability to speak is as difficult to diagnose as it is to cure

WORDS: **HAYLEY BENNETT**



SCIENCE PHOTO LIBRARY

"When I was diagnosed with motor neurone disease in 2003, my consultant offered Stephen Hawking's example as a positive case," writes Euan MacDonald, from his Edinburgh home. "I have to say that gave me no comfort at all."

While MacDonald admired Hawking's achievements, back then the prospect of living like him "seemed like a nightmare". Both, unusually, were diagnosed in their twenties – it's more common for people to be diagnosed with motor neurone disease (MND) in their fifties. As his disease progressed over the next 15 years MacDonald's mobility and speech deteriorated. He gained a ventilator connected to a tracheostomy (a hole in the front of his throat) to help him breathe and an eye gaze device. He can't write or talk in the conventional way, but the eye gaze device tracks the movements of his eyes across a screen and allows him to type. It can also turn his words into speech. Hawking had a similar device that in his final years he operated with his cheek.

In some people with MND, speech is affected very early on and slurring can be one of the first clues, while in others it starts with a twitching in the arms and legs. Either way, speaking, swallowing and eventually breathing become difficult. That's because the muscles in the face, throat, tongue and diaphragm are under the control of motor neurones, the nerves responsible for movement that degenerate in MND sufferers. In the most common form of the disease, called amyotrophic lateral sclerosis (ALS), all the motor neurons are affected, although there are other forms in which those originating in the brain or those connecting to the muscles are spared.

> **"The symptoms don't show up straight away because nerves are very good at compensating for any neighbours that stop working"**

Brian Dickie, director of research development at the MND Association, describes it like "trees burning in a forest fire". As the fire takes hold, the nerves fail and the muscles connected to them wither away. Progress can be rapid, with patients quickly becoming wheelchair-bound. Most people with MND live no longer than three years from the time of their diagnosis. Hawking was peculiar in that his version of the disease allowed him to live for decades, and MacDonald now counts himself as "one of the lucky ones".

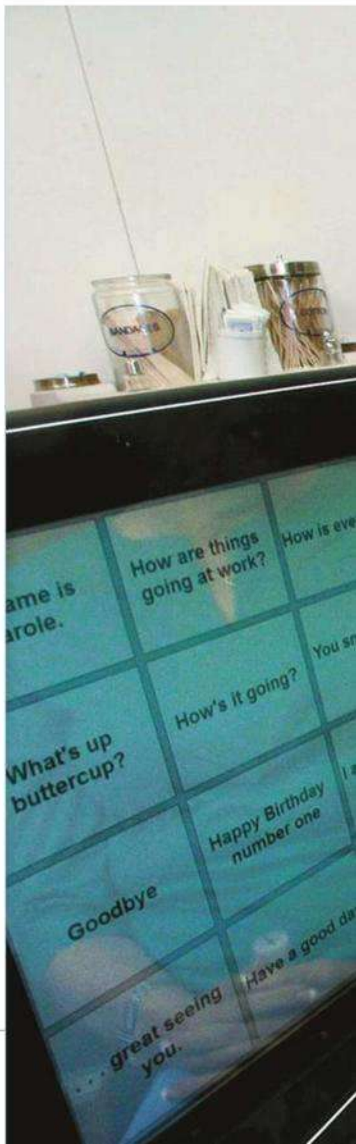
Making a timely diagnosis is one of the first challenges that doctors face when they see someone they suspect might have MND. By the time that person is referred to a neurologist, the disease may have already ravaged half of their motor neurones. The symptoms don't show up straight away, explains Dickie, because nerves are very good at compensating for any neighbours that stop working. It's only when the remaining ones become overloaded that things start to go awry. Then, because there's no definitive test for MND, it's a case of ruling out a long list of other diseases it might be.

"People undergo many, many tests, but they're to exclude other things, until they're finally left with MND at the bottom of the list," Dickie says. "So it does mean that by the time patients are even given a name for the disease, they're pretty far down that slippery slope." It's not uncommon for it to take a year to diagnose MND, in a patient who might only live another 12 months. Hawking wasn't expected to survive even five years from he was diagnosed aged 21.

TEAMWORK AND TECH

Besides one drug that can extend life for a few months, there's no medication available that has a proven impact on the progress of the disease, so treatment for an MND patient is about improving their quality of life. In the UK, once the diagnosis is confirmed, patients are assigned a group of specialist nurses or occupational therapists, who assess their physical and mental health. This team, trained in neuroscience as well as palliative care, supports the patient and their family through the entire process, working with community carers to look after their everyday needs.

"The [team] is expert in assessing people living with neurodegenerative diseases and highly specialised in dealing with patients and families who may be distressed by their diagnosis," says Judith Newton, national nursing lead for MND, based at the University of Edinburgh. It also plans ahead for equipment requirements such as



EUAN MACDONALD CENTRE, GETTY

LEFT: Since being diagnosed with motor neurone disease in 2003 Euan MacDonald has set up a research centre for the disease at the University of Edinburgh

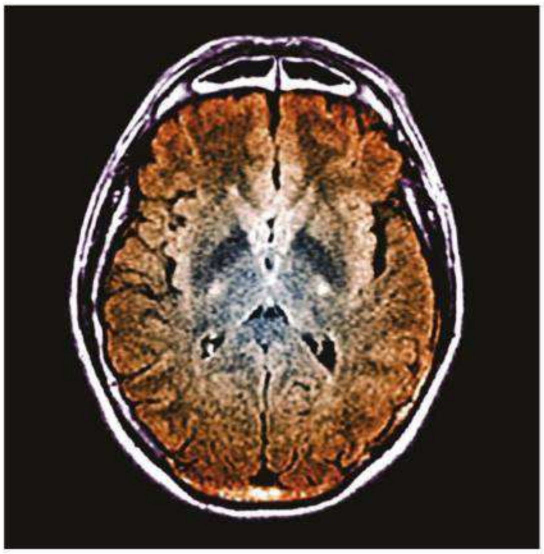
BELOW: A speech pathologist trains Jocelyn Odom (right) to use the technology that will enable her to commnicate after her speech is lost to motor neurone disease

wheelchairs and communication aids, including MacDonald's eye gaze device. Planning ahead is essential for those who experience rapid progress of their symptoms, but as Hawking demonstrated, progress of MND can also plateau for many years and in these cases, specialist equipment becomes part and parcel of life.

For these long-lived patients, staying connected to the world can improve their state of mind. MacDonald writes that while he has had struggles and difficult times, he's not living the nightmare he anticipated, and says that's at least partly down to his ability to stay connected.

"The most crucial piece of equipment I have, along with my ventilator, is my communication device – life wouldn't be possible without it," he says. "This is one case where technology definitely changes lives for the better."

In the 15 years since his diagnosis, MacDonald has been far from idle. He established a centre for MND research at the University of Edinburgh and, just five years ago, set up euansguide.com, a reviews website that provides information about



"We should be looking at these long-term survivors and trying to find out if there's some genetic factor"

access and facilities for disabled people. He's also involved in the Speak:Unique Voicebank research project, which is recording the voices of people with MND so that in future they could be used, via voice synthesisers, by those who've lost the use of their vocal chords.

ABOVE RIGHT: Motor neurone disease causes a rapid degeneration of the cells in the brain that control movement

BELOW: Professor Ammar Al-Chalabi thinks that there are about six biological steps on the way to nerve degeneration. Knocking out one of those steps may be a way to diminish MND's effects or prevent it altogether

GENETIC AND VIRAL FACTORS

Those who live a long time with the disease, like Hawking and MacDonald, are increasingly drawing the attention of geneticists, according to Dickie. "They think maybe we should be looking at these exceptionally long-term survivors and trying to find out if there's some genetic factor or series of genetic factors, because if we can identify [them], that gives us a more direct route into potential treatment."

In the last quarter of a century, geneticists have taken huge strides in characterising the genetic landscape of MND, beginning with a gene called SOD1 in 1993. Over 120 genetic variations associated with the disease have since been discovered. Now, with money raised by the ALS Ice Bucket Challenge (remember when everyone was filming themselves tipping buckets of iced water over their heads?), researchers are sequencing the genomes of 15,000 patients.

The perplexing thing is that not everyone who has MND carries the same genetic factors for it and people with the same genetic factors may have quite different symptoms or even completely different diseases. For example, some people with the C9ORF72 gene variant have typical MND, while others have Parkinson's disease. To complicate matters further, scientists think that lifestyle factors probably have an important impact too – they just don't know which ones.

Ammar Al-Chalabi, a consultant neurologist at King's College London, suggests that MND could be caused by a multi-step biological pathway, where each step on the path has to be taken before the nerves start degenerating. In a paper published in 2014, Al-Chalabi and colleagues from around the world used 25 years worth of data from over 6,000 MND patients and some complex mathematical modelling to determine how many steps that pathway might have.

"You've got six molecular steps that are needed before it develops," he says. This could explain why certain MND-associated gene variants seem to cause disease in some people but not others – perhaps they only become troublesome if other steps in the pathway also come into play at the right time. The idea is attractive because it would mean the disease could be prevented by knocking one step out of the sequence or eliminating a single risk factor.

Of course, the difficulty is pinning down all the possible steps. One emerging theory concerns

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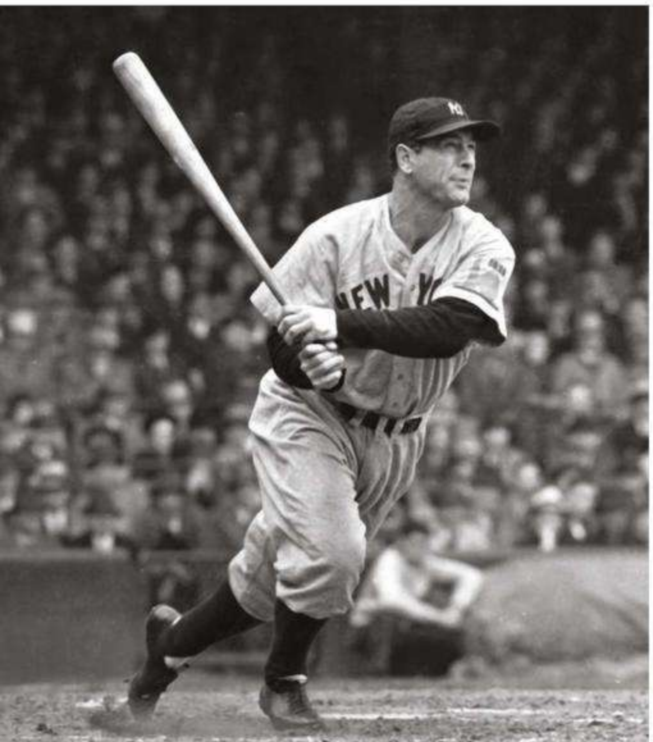


ABOVE: Money raised by the ice bucket chellenge was used to fund a research project into the genetic variations that play a role in amyotrophic lateral sclerosis (ALS), the most common form of MND

LEFT: Lou Gehrig had a storied career playing baseball for the New York Yankees until ALS (now known as Lou Gehrig's disease) forced him to retire in 1939

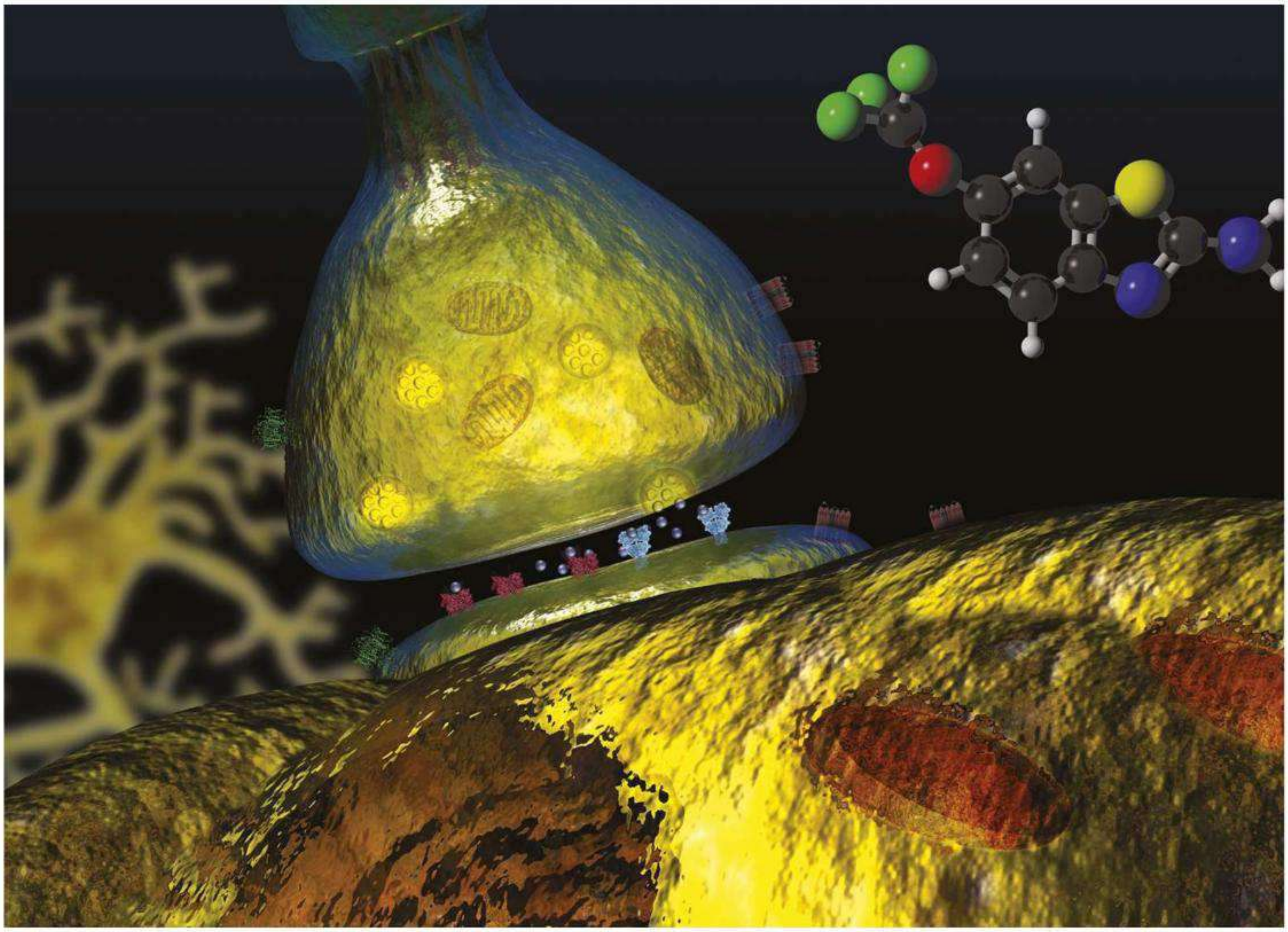
endogenous retroviruses. These are remnants of viruses that infected us thousands of years ago lurking in the human genome. DNA from retroviruses, which are related to HIV, is actually pretty common, making up as much as five to eight per cent of the human genome. In theory, reactivation of these long-dormant viruses could form one link in the chain of molecular events responsible for disease.

According to Al-Chalabi, there's already evidence that this happens in a certain type of mouse. "The only ones that get MND," he says, "are the ones who have an endogenous retrovirus combined with a gene variant that makes it very active and who are then infected with another virus. If they get all three hits, they get the disease. So you can imagine how retroviruses might work but they wouldn't be enough on their own."

HOPE AND THE HAWKING ASPECT

Getting to the root of what causes MND is driving research into potential new treatments. With a clearer picture of the specific factors

Hawking lived for an exceptionally long time with MND and achieved a great many things during that period. Here, the physicist is seen during a visit to CERN in Switzerland



ABOVE: the drug riluzole (seen in its molecular form, top right) blocks the action of the neurotransmitter glutamate (under the bell shape) to slow the progress of MND

that trigger MND in one person but not another, it might eventually be possible to offer a more personalised treatment that could deal with an individual's particular version of the disease. It's like knowing someone's blood type before you give them a blood transfusion, explains Al-Chalabi.

For the moment, however, there's riluzole – the drug that extends life for a few months – and a drug called edaravone that's only approved for MND in the US and Japan. It's no longer clear how riluzole works, after recent results tossed its proposed mode of action up in the air. Meanwhile, trials are ongoing with drugs that work in a variety ways. One trial, for example, is using a cancer drug to try to alter the activity of glial cells in the brain, which seem to play a role in dictating how fast the "forest fire" of MND spreads through the nervous system.

"Given the lack of effective drugs, it's unlikely that anything Hawking was taking helped him to live so long"

Given the lack of effective drugs, it's unlikely that anything Hawking was taking helped him to live so long. "It's more likely to be the particular form of the disease," says Dickie. "We know that between five and 10 per cent will live for 10 years or longer. Clearly he was one extreme end of the spectrum." He adds that Hawking was perhaps the best and worst example of MND. The best because of everything he achieved, but the worst because he was such an unusual case. Many people still don't realise that MND is nearly always a rapidly progressive, terminal condition.

Dickie suggests that in cases like Hawking's there are "good genes" that help the patient push back against the disease to survive for longer. Perhaps MacDonald has some of those too. For him there's also relief – a treatment, of sorts – in the technologies he uses to help him interact with the world. He has a voice, one synthesised from his own and his brother's, and 24/7 access to the internet, email and Skype. "My face is buried in a screen all day – just like everyone else!" he jokes.

As for Hawking, how does he feel about him now? "Stephen Hawking was just one example of someone living with MND and doing fantastic things," he writes. MacDonald is another.

CERN, SCIENCE PHOTO LIBRARY

ANDRE PATTENDEN

Part Two

HAWKING'S WORK

Few people see the Universe in the same way as Stephen Hawking did – as an intriguing puzzle. But a puzzle that could be solved, as long as you were prepared to devote enough thought and determination to the challenge

Singularities – WHERE THE LAWS OF PHYSICS BREAK DOWN P50

Black Holes – AN INESCAPABLE DRAW P54

No-Boundary Universe – BEFORE THE BEGINNING P66

Hawking's Final Prediction – SCALING DOWN THE MULTIVERSE P70

SINGULARITIES

Whenever a singularity crops up in an equation, you've got a problem. But when Hawking's early work addressed the problem of the singularity in Einstein's equations, it led to some amazing breakthroughs

WORDS: **MARCUS CHOWN**

A singularity is a monstrous thing. If one crops up in a mathematical equation, the quantity it represents sky-rockets to infinity, and the equation becomes nonsensical. The trouble is, a singularity appears in the equations that describe the birth of the Universe: Einstein's theory of gravity.

In the early 1960s, a young Cambridge postdoctoral student called Stephen Hawking was contemplating this, and it worried him deeply. Hawking had become fascinated with cosmology, the science that deals with the origin, evolution and fate of the Universe. In 1917, Albert Einstein – never one to think small – had applied his brand new theory of gravity, also known as the General Theory of Relativity, to the biggest gravitating system he could think of: the entire Universe. Like his predecessor, Isaac Newton, however, he was wedded to the idea of a static Universe, in which the stars and galaxies hung in space, unchanging, for all time. Einstein therefore missed the message in his own equations, which was that the Universe was inherently restless and had to be in motion.

GETTY

FROM EINSTEIN TO HAWKING

In the 1920s, this was spotted independently by Russian physicist Aleksandr Friedmann, and Belgian physicist and Catholic priest George Abbé Lemaître. The evolving universes the two men discovered lurking in Einstein's equations were christened Friedmann-Lemaître universes. Nowadays, however, pretty much everyone uses another term for them: Big Bang universes.

Observational proof that we did indeed live in an evolving Universe came in 1929. Working

"The question was: was it possible to avoid the catastrophic singularity at the beginning of time? There was one possibility..."

at what was then the biggest telescope in the world, the 100-inch Hooker Telescope on Mount Wilson near Los Angeles, American astronomer Edwin Hubble discovered that the Universe was expanding, its building blocks – galaxies of stars, such as our own Milky Way – flying apart from each other like pieces of cosmic shrapnel in the aftermath of a titanic explosion.

If the expansion of the Universe were imagined running backwards, like a movie in reverse, a moment is reached – now known to be 13.82 billion years ago – when all of matter is squeezed into a tiny volume. This is the moment of the Universe's birth: the Big Bang.

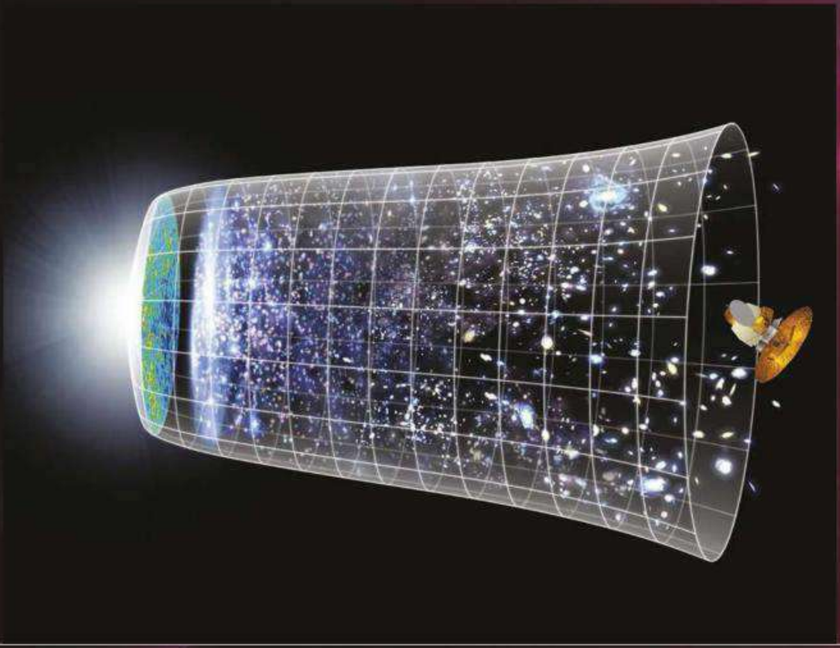
A Universe that simply popped into existence one day was deeply unattractive, and most scientists in the early 1960s did not believe the Big Bang idea. Fortunately, there was a way to avoid it. If, as galaxies fly away from each other, new matter fountains into existence out of the vacuum, it can congeal into new galaxies to fill the gaps. Despite expanding, the Universe can still look the same at all times and so be infinitely old, avoiding the embarrassing "what happened before the Big Bang?" question. But this 'steady state' theory, championed by British astronomer Sir Fred Hoyle, would be dealt a killer blow by the discovery in 1965 of the cosmic microwave background, the radiation 'afterglow' left behind by the Big Bang fireball.

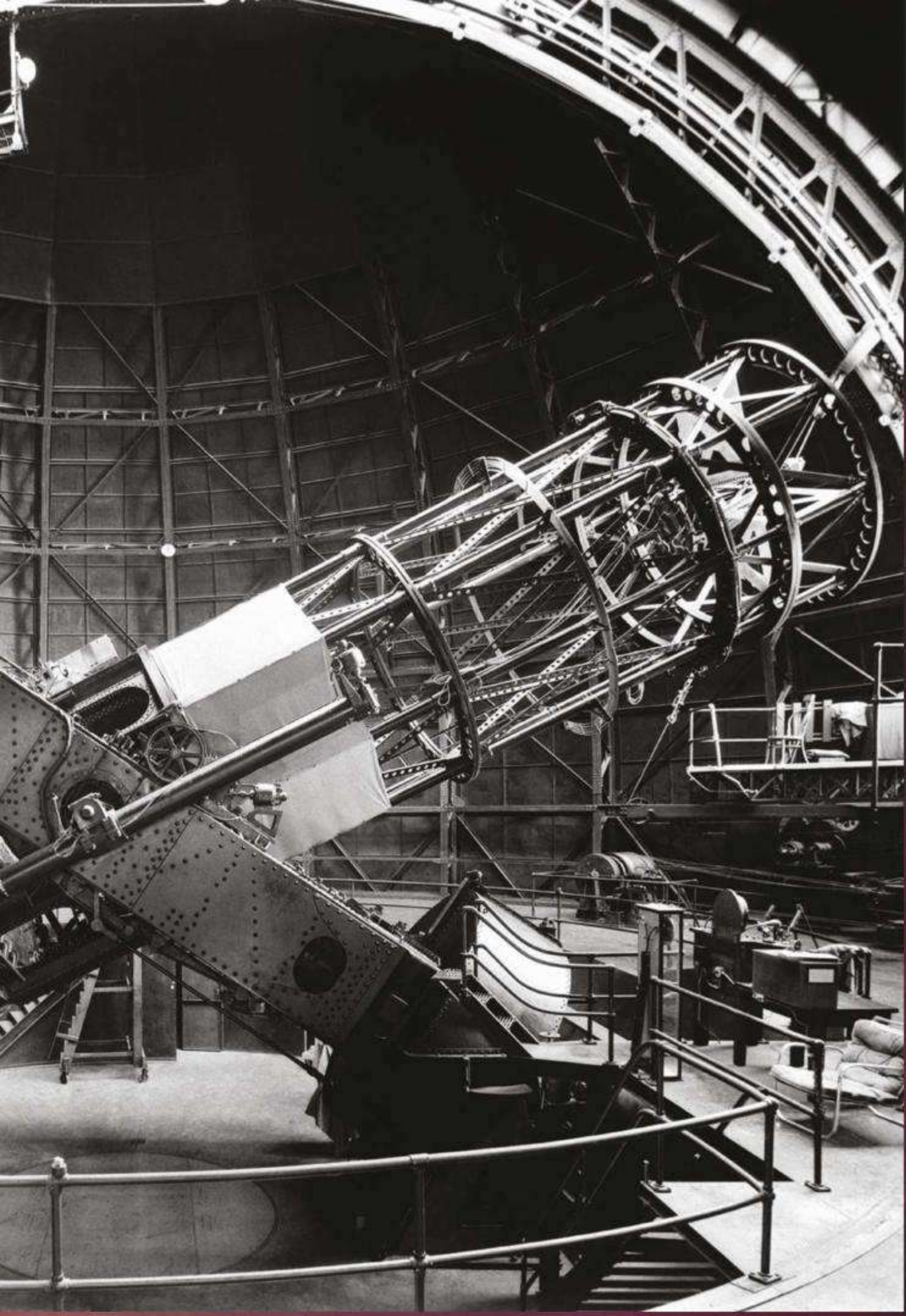
This, then, was the scientific background as Hawking embarked on his post-PhD research. In his mind, he imagined the expansion of Universe running backwards. As the Universe shrinks ever smaller, matter is squeezed ever more tightly. As anyone who has squeezed the air in a bicycle pump knows, it gets hotter. The Big Bang, as others had also realised, was therefore a hot Big Bang. However, according to Einstein's theory, this process has no limit. As the Universe dwindles to a point, its temperature and density sky-rocket to infinity. By predicting such a singularity, Einstein's theory therefore has nothing sensible to tell us about the ultimate origin of the Universe.

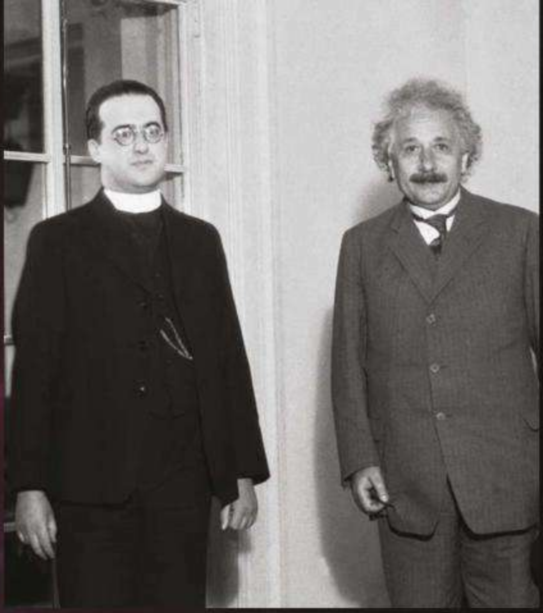
AVOIDING CATASTROPHE

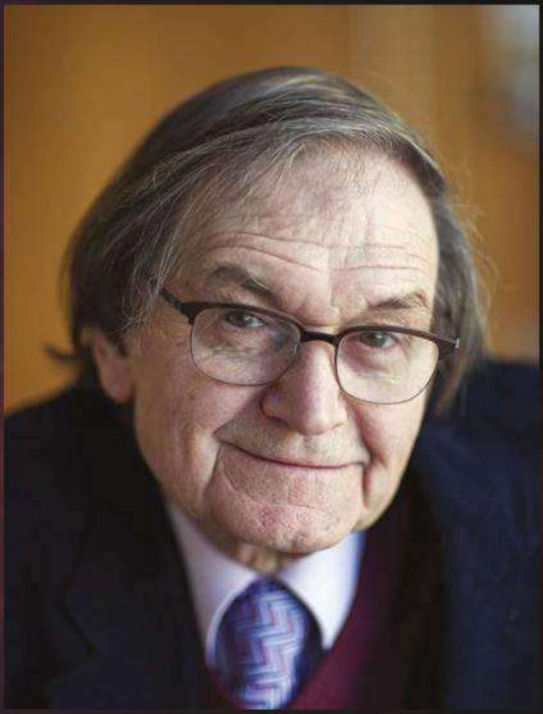
This was the problem. The question was: was it possible to avoid the catastrophic singularity at the beginning of time? There was one possibility. If the matter of the Universe were spread unevenly, this unevenness would become magnified as the backward-running universe shrunk ever smaller. Different parts of the collapsing Universe, instead of all piling up at one point, might miss each other and so not create a singularity.

Since Einstein's theory of gravity would not break down, it would be possible to follow the history of the Universe to earlier times – before the Big Bang. Perhaps, for instance, the Universe









ABOVE: The 100-inch Hooker Telescope in California, which Edwin Hubble used in the 1920s to prove that the Universe was expanding

TOP RIGHT: George Abbé Lemaître with Albert Einstein. Lemaître's ideas were crucial to the evolution of the Big Bang theory

ABOVE RIGHT: Roger Penrose, the British mathematician who worked with Hawking on some of his key early discoveries

FAR LEFT: The evolution of our Universe since the Big Bang, as we currently understand it

LEFT: Russian physicist Aleksandr Friedmann, who was working on similar ideas to Lemaître at roughly the same time

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had contracted down to a 'big crunch' from which it had then bounced in the Big Bang. While working on such matters, Hawking's colleague Brandon Carter happened to mention a talk he had attended in London, given by a young mathematician called Roger Penrose. It seemed Penrose was using novel topological methods to investigate the formation of another type of singularity, one which formed at the heart of a black hole – the region of grossly warped space-time left behind when a dying star shrinks catastrophically under his own gravity. A black hole singularity was a singularity in space rather than time, but it had much in common with the singularity of the Big Bang.

Hawking contacted Penrose. It was the start of one of the most fruitful collaborations in 20th-century physics. Between 1965 and 1970, the pair proved a range of powerful singularity theorems. The most important was that, under a wide range of general and highly plausible conditions, the singularity in the Big Bang was unavoidable. It would form, they showed, no matter how the backwards-running movie of the Universe played out.

QUESTIONS REMAIN...

Since a singularity is nonsensical, Hawking and Penrose had shown that Einstein's theory contains the seeds of its own destruction. Just as Newton's theory of gravity proved to be an approximation of a deeper theory – Einstein's – Einstein's theory of gravity, in turn, is an approximation of a yet deeper theory. The deeper theory, dubbed quantum gravity, has so far eluded physicists. Only when it is found will be able to answer the biggest question of all: where did this Universe we all live in come from?

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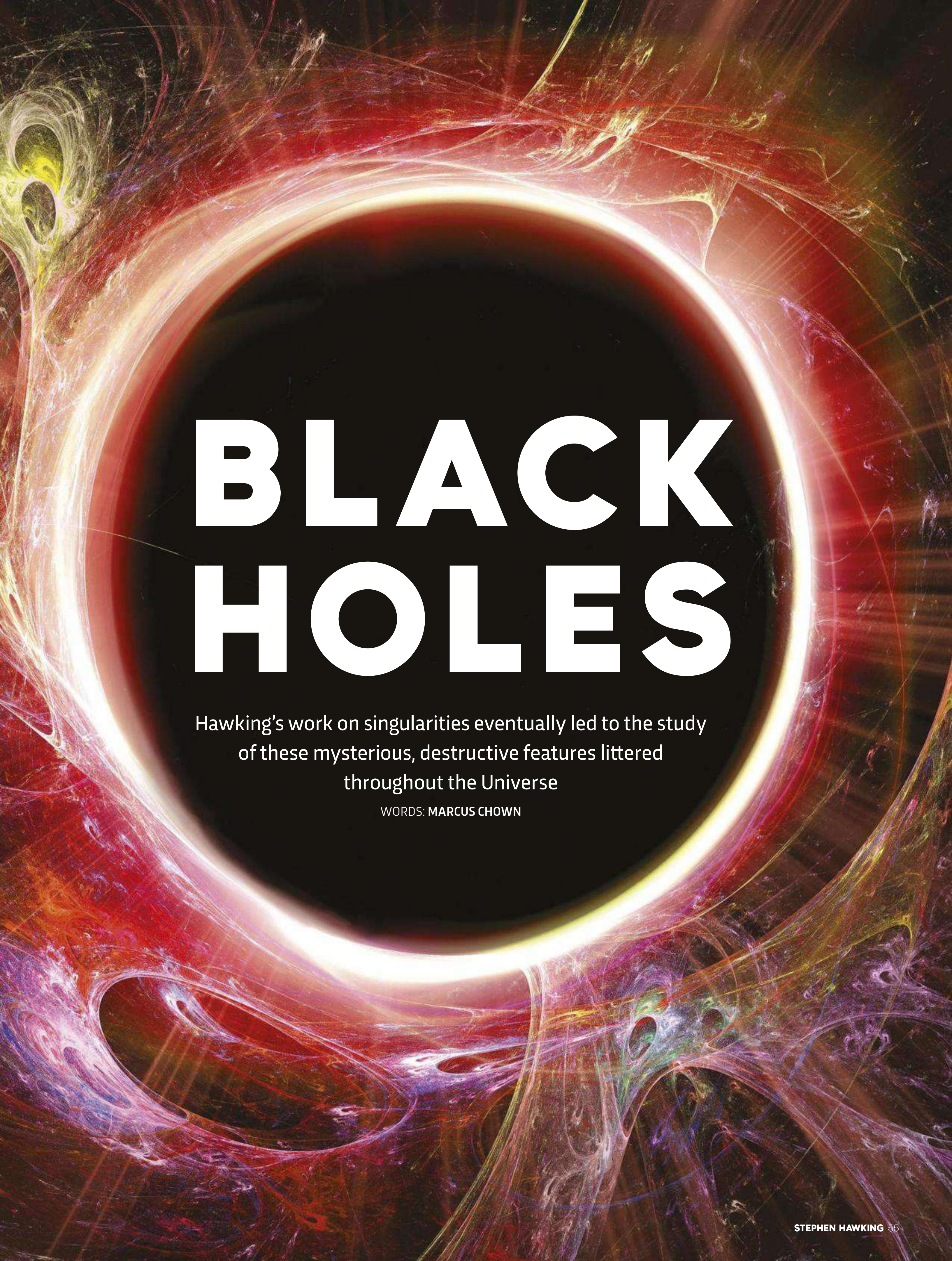

BLACK HOLES

Hawking's work on singularities eventually led to the study of these mysterious, destructive features littered throughout the Universe

WORDS: **MARCUS CHOWN**

The Sun is not hot. The deceased are not actually dead. *Mrs Brown's Boys* is hilarious. Anyone who can turn on its head the central characteristic of what we know about anything will earn their place in history. And that's exactly what Stephen Hawking did when, in 1974, he showed that, contrary to all expectations, black holes are not black.

Black holes are a consequence of Einstein's General Theory of Relativity, which he announced to the world in a series of lectures in Berlin in November 1915. Whereas Isaac Newton imagined a force of gravity, like an invisible tether that connects the Earth to the Sun and keeps the Earth trapped in orbit, Einstein showed that this is wrong. There is no such force. Instead, a mass like the Sun creates a valley in the space-time around it, and the Earth's natural motion is to travel around the upper slopes of the valley like a roulette ball around a roulette wheel.

American physicist John Wheeler distilled Einstein's theory down to a simple statement: "Matter tells space-time how to warp. And warped space-time tells matter how to move." We do not perceive the curvature of space-time because it is a four-dimensional thing and we are lowly three-dimensional beings. That's why it took a genius like Einstein to notice.

Einstein's theory replaces the one equation of Newton's universal theory of gravity with 10 equations. Finding solutions – the shape of space-time created by a given distribution of matter – is therefore extremely difficult. So difficult, in fact, that anyone who finds a solution invariably gets their name attached to it. Remarkably, however, one man discovered a solution within only months of the publication of General Relativity.

German physicist and astronomer Karl Schwarzschild (1873-1916) was the first person to solve the equations of General Relativity for a particular object

ABOVE: John Wheeler (right) with Albert Einstein and the first Japanese Nobel laureate, Hideki Yukawa, in 1954

LEFT: John Archibald Wheeler (1911-2008) in his office at Princeton. Wheeler, one of the first scientists to really get to grips with Einstein's theories, would go on to help develop both nuclear power and the atomic bomb, as well as coining the term 'wormhole'

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Karl Schwarzschild was a German Jew who wanted to show anti-Semites that Jews were patriotic too. So, despite being 40, he signed up for the army the moment the First World War began. In his 18 months in the Kaiser's army, he ran a weather station in Belgium, calculated shell trajectories with an artillery battery in France and served in Russia. It was there that he contracted *pemphigus vulgaris*, a debilitating disease in which his immune system attacked his skin, covering him in painful weeping blisters. Within months, it killed him. However, while laid up in a hospital on the Eastern Front, with the constant thump of distant guns, he digested Einstein's new theory and began to think.

BEYOND EINSTEIN

Schwarzschild considered a spherically symmetric mass such as a star. He made a number of simplifying assumptions, which greatly cut down the number of Einstein's equations, and was amazed to be able to find the precise way in which space-time curved in the vicinity of such a mass. But not as amazed as Einstein, in Berlin, when he opened a letter from the Eastern Front to find what would become known as the Schwarzschild solution.

Both Schwarzschild and Einstein noticed that, if a mass were squeezed into a very small volume, the valley of space-time would become so steep it would turn into a bottomless well out of which nothing, not even light, could escape. Since it would require squeezing the Sun into a volume only 6km across, which both men considered

ridiculous, they missed out on predicting black holes, a term that would be popularised by Wheeler only in 1967.

Other physicists agreed that, before a mass could shrink within its Schwarzschild radius to become a black hole, some other force of nature must surely intervene to prevent such a catastrophe. However, in 1930, a 19-year-old Indian mathematical prodigy called Subrahmanyan Chandrasekhar showed that, if a very massive star exhausted its fuel and could no longer generate enough internal heat to oppose the gravity trying to crush it, no known force could prevent its runaway collapse to form a black hole. Having blinked out of existence, in fact, the star would continue shrinking down to a point of infinite density known as a singularity [see 'Singularities', p50].

A singularity would signal the breakdown of physics. Surely nature would not permit the existence of such a monstrosity? However, in 1971, the first stellar-mass black hole, Cygnus X-1, was discovered by Paul Murdin and his colleagues using NASA's Uhuru X-ray satellite. And, actually, black holes – of a very different kind – had been stumbled on almost a decade earlier in 1963.

ABOUT SCHMIDT

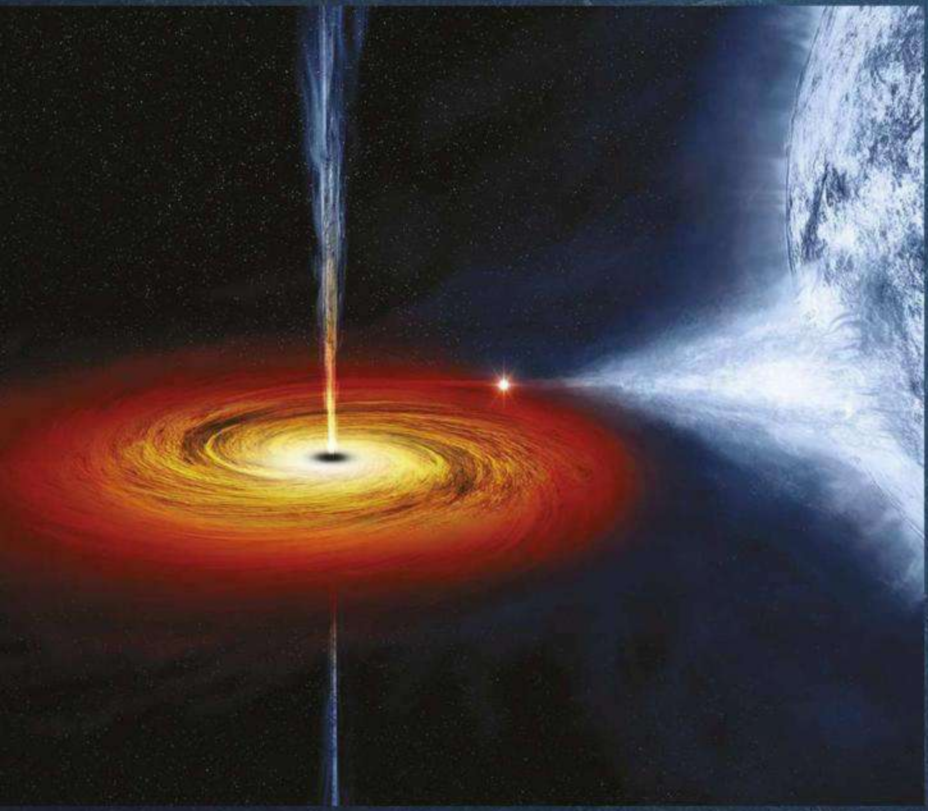
Quasars, discovered by Dutch-American astronomer Maarten Schmidt, were the super-bright cores of newborn galaxies. Typically, they pumped out 100 times the energy of a galaxy of stars, but from a volume smaller than the Solar System. The only possible source of such prodigious luminosity was matter, heated to incandescence, as its swirled like water down a plughole into a black hole. But not a stellar-mass hole – one with a mass up to 50 billion times that of the Sun.

Initially, it was thought that such supermassive black holes powered only active galaxies, the one per cent of unruly galaxies of which quasars are the most striking example. But, in the 1990s, astronomers using NASA's Hubble Space Telescope in Earth orbit discovered that there is a supermassive black hole lurking in the heart pretty much every galaxy. The one in the core of our Milky Way, known as Sagittarius A*, is a tiddler, weighing in at only 4.3 million times the mass of the Sun. *Why* there is a supermassive black hole in every galaxy remains one of the great unsolved mysteries of cosmology.

But, if the discovery by observational astronomers of actual black holes across the Universe was a shock, it was nowhere near as shocking as the properties of black holes, which were laid bare by theoretical physicists. And this is where Hawking comes into the story.

> "A singularity would signal the breakdown of physics. Surely nature would not permit the existence of such a monstrosity?"

OPPOSITE: Carrying out pre-flight checks on NASA's Uhuru X-ray satellite (also know as SAS-1) at the Goddard Flight Center, Maryland in 1970



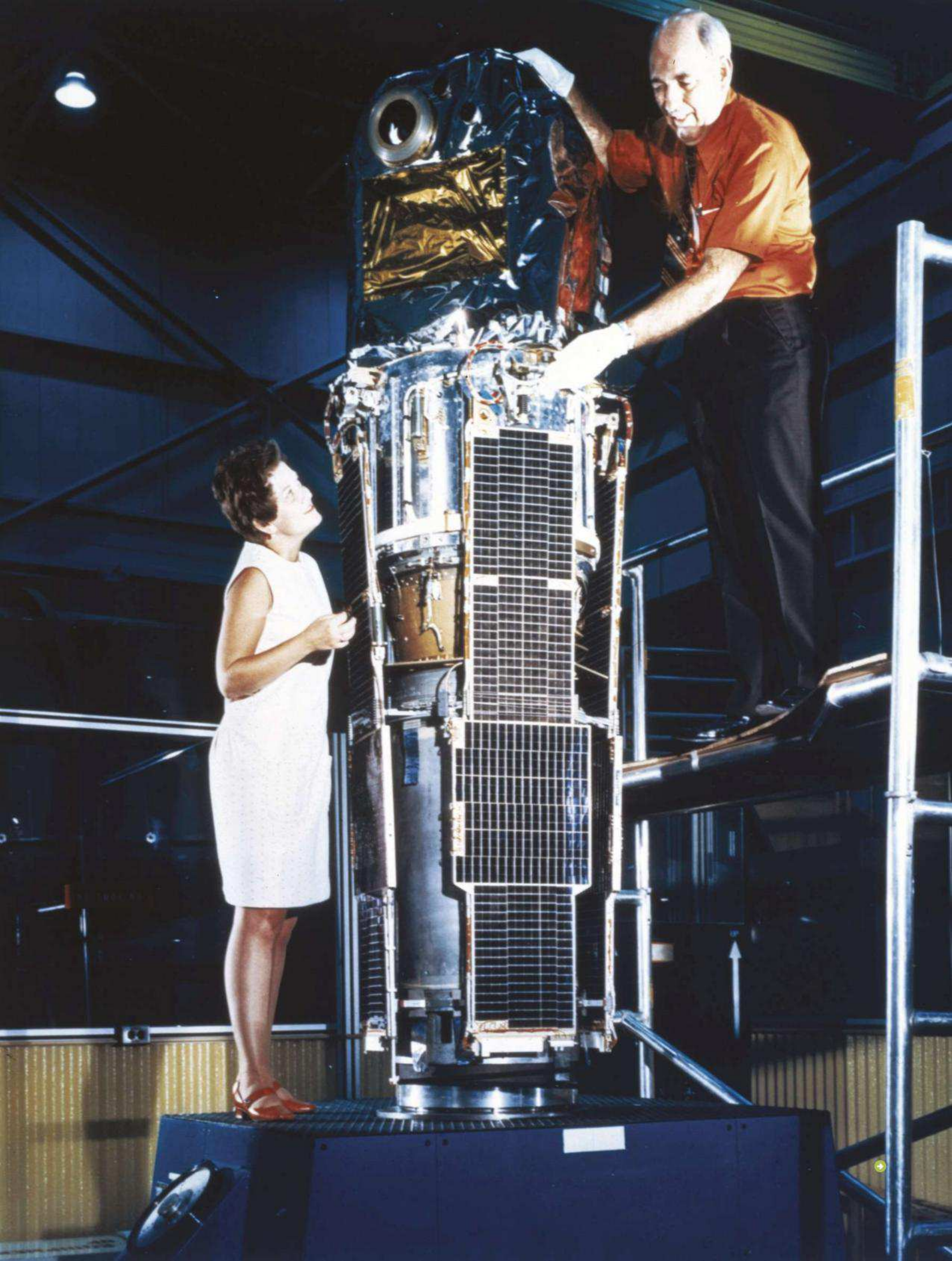
BELOW: Artist's impression of activity in the region of Cygnus X-1, the first stellar-mass black hole ever discovered. Matter is being drawn from the star and then 'swallowed'

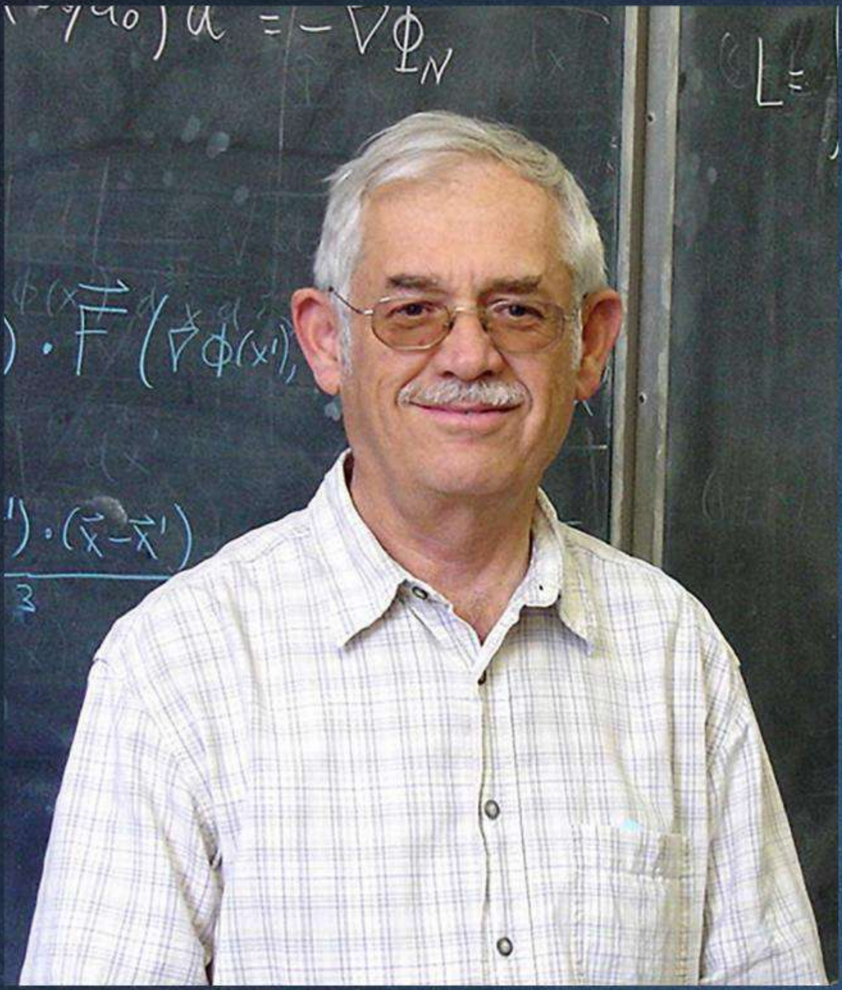
NASA/CXC/M WEISS, GETTY

HAWKING'S CONTRIBUTION

Hawking turned his attention to black holes after his work with Roger Penrose on the Big Bang singularity. Along with other physicists, he proved a range of theorems about these cosmic vacuum cleaners. Most striking was the discovery that, regardless of what the star that shrunk down to form a black hole looked like, the final black hole was essentially characterised by just two things – its mass and how fast it was spinning. Black holes are breathtakingly simple. As Chandrasekhar, who won the 1983 Nobel Prize for Physics, observed: "The black holes of nature are the most perfect macroscopic objects there are in the Universe: the only elements in their construction are our concepts of space and time."

Hawking's next and most famous work built on the insight he and Penrose had gleaned about the Big Bang. The fact that Einstein's theory broke down at a singularity did not mean the





ABOVE: Jakob Bekenstein at the Hebrew University in Jerusalem, 2009. His work on black holes and entropy led indirectly to Hawking's discovery of Hawking radiation

OPPOSITE: To finally 'see' Hawking radiation, we'll need to send probes into distant supermassive black holes – or somehow recreate similar conditions right here on Earth

beginning of the Universe was forever beyond scrutiny. It simply meant that something better than Einstein's theory was required in order for us to penetrate to this remote time. That something was widely believed to be quantum theory, the theory of atoms and their constituents that explains why the ground under our feet is solid and the Sun shines, and that has given us lasers, computers and nuclear reactors. The problem was that no one knew how to fit together quantum theory and Einstein's theory: in fact, unifying them is to this day *the* outstanding unsolved problem in physics.

Hawking's intention was to attack the singularity in the Big Bang and at the centre of a black hole, using quantum theory to lift the opaque curtain that the singularity effectively dropped across our view. But that problem was going to be a hard nut to crack. So Hawking decided to practise on an easier problem.

ON THE HORIZON

The singularity at the heart of the black hole is actually cloaked by its event horizon (characterised by the Schwarzschild radius). This marks the point of no-return for matter falling into a black hole: pass beyond the event horizon and you can never get out again. It is the horizon that astronomers think of when they talk about the size of a black hole.

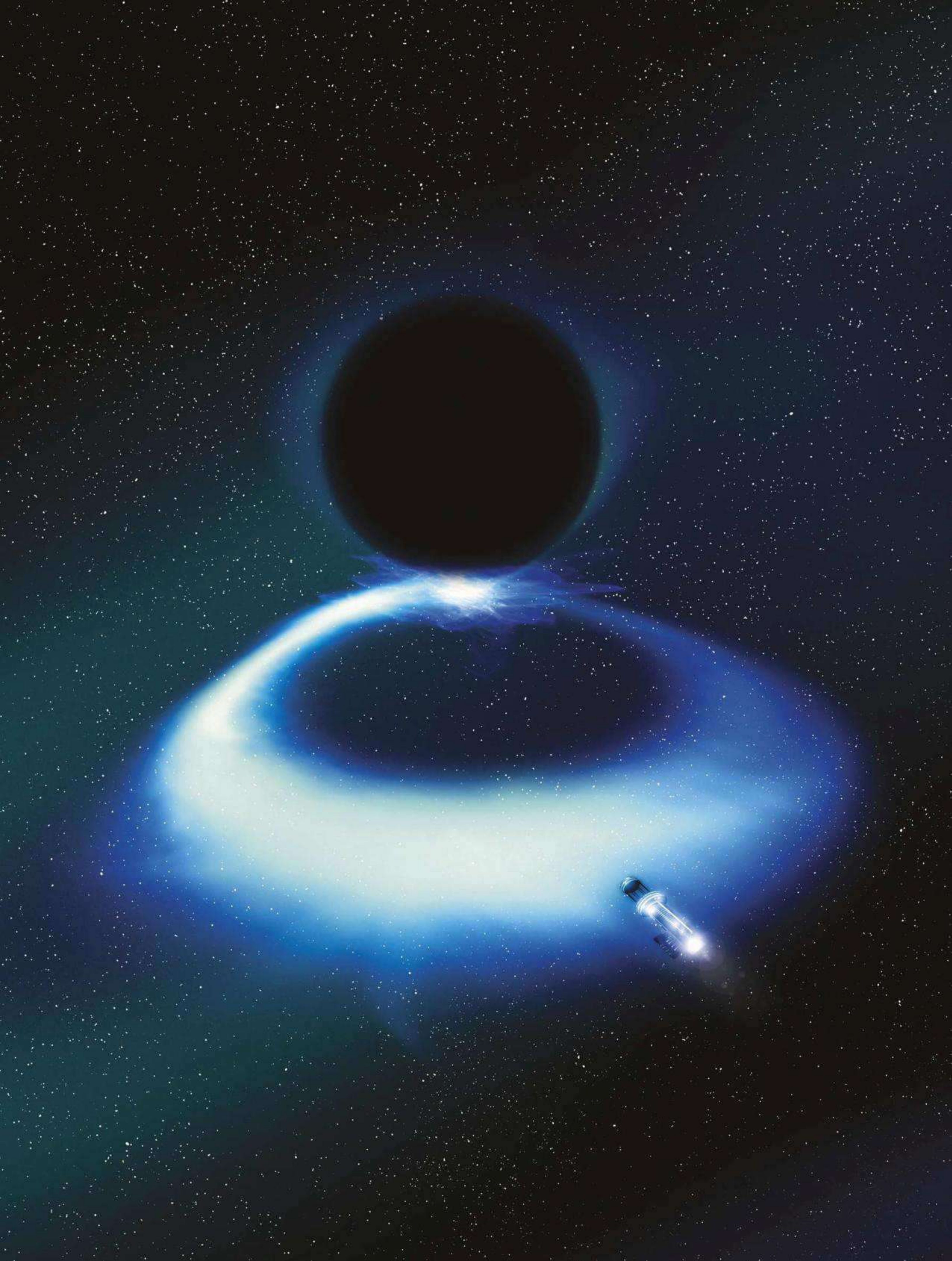
In 1974, Hawking discovered something remarkable – and to physicists, scarcely believable – about the event horizon. To appreciate it, it's necessary to understand what quantum theory says about empty space. Far from being empty, it's actually seething with energy. Specifically, subatomic particles and their antiparticles are continually popping into existence in pairs, something permitted by the Heisenberg Uncertainty Principle. Nature turns a blind eye to these particles – not bothering about where the energy to create then comes from – just as long as they meet and destroy, or annihilate, each other very quickly. It's a bit like a teenager borrowing their Mum's car but getting it back in the garage before she notices it's missing.

But, as Hawking realised, near the horizon of a black hole something interesting happens. There's the possibility that one of the particles of a newly created pair falls through the horizon into the black hole. The remaining particle has no partner to annihilate with and flies away from the hole, along with countless others in the same situation. Contrary to all expectations, therefore, black holes are not totally black. They glow with emitted particles – or Hawking radiation.

One of the black hole theorems that Hawking had discovered earlier was that, when black holes merge, the surface area of the horizon of the merged hole is always bigger than the sum of the areas of the two precursor black holes. The Israeli physicist Jacob Bekenstein had speculated that the surface area represents the entropy of the black hole. This is a property that arises in the theory of thermodynamics – the theory of heat and motion that underpins physics and chemistry and many other fields – and which always increases. But it applies only to hot bodies. How could it possibly apply to a black hole?

Hawking had found the answer: thermodynamics applied to black holes because they're hot! They

"Far from being empty, space is actually seething with energy. Specifically, subatomic particles and their antiparticles are continually popping into existence in pairs"



NEEDLE IN A HAYSTACK

All about the Event Horizon Telescope

In the latter years of his life, Hawking came up with another radical new idea about black holes: that they aren't actually black at all. He suggested that rather than having an event horizon from which nothing can escape, they may have only an apparent horizon, from which nothing *seems* to.

To ascertain if this is true, we're going to need a bigger telescope. The Event Horizon Telescope is an ongoing project to build just such a thing, but it's not actually a single 'scope you can peer through. Rather, the EHT will work by combining data from multiple radio observatories around the world. The job of crunching all that data will be handled at MIT's Haystack Observatory in Massachusetts, and at Germany's Max Planck Institute for Radio Astronomy.

ABOVE: String theory, which imagines all matter and energy in the Universe as being made up long, vibrating strings, is our current best candidate for a unifying theory of everything

have a temperature. The proof was that they glowed with heat – Hawking radiation. The significance of Hawking's discovery was that, at the horizon of a black hole, three of the great theories of physics meet: Einstein's theory of gravity, quantum theory and thermodynamics. A first tentative step had been made on the road to uniting them – the Holy Grail of physics. However, Hawking radiation threw up a serious problem, a puzzle whose resolution could signal the next step on the road.

Particles of Hawking radiation don't come from inside a black hole since, of course, nothing can escape its gravity. Instead, they're created just outside the horizon. The energy to create them has to come from somewhere, and it comes from the gravitational energy of the black hole itself. As it radiates Hawking radiation, it therefore gradually shrinks away.

Star-sized black holes have extremely weak Hawking radiation but, as a black hole gets smaller, the radiation gets brighter until, finally, the hole explodes in a blinding flash. Since such 'evaporation' would take far longer than the current age of the Universe, it might seem of no consequence. However, nothing could be farther from the truth.

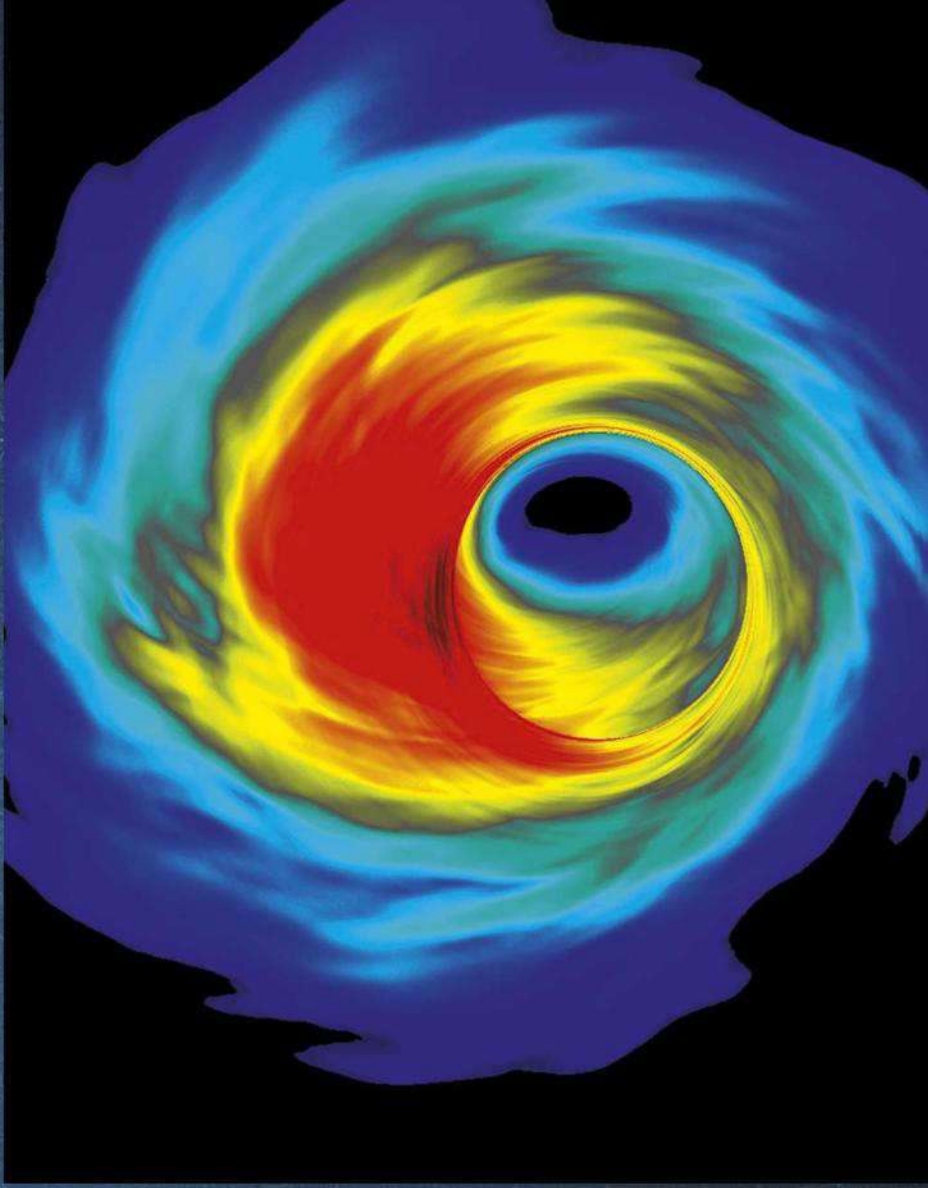
It's a cornerstone of physics that information cannot be destroyed. A complete description of the star that initially collapsed to form a black hole would require recording the type and position of each of the huge number of subatomic particles that compose it. But, once a hole has evaporated, there's literally nothing left. Where does all that information go?

WHERE HAWKING WENT WRONG

In trying to resolve this question – known as the black hole information paradox – Hawking was driven to desperate lengths, which later embarrassed him. "I used to think information

"In trying to resolve the question known as the black hole information paradox, Hawking was driven to desperate lengths"

DADEROT/WIKIPEDIA, GETTY, SCOTT NOBLE/RIT



was destroyed in black hole," he said. "This was my biggest blunder."

In 1993, Dutch Nobel Prize-winner Gerard t'Hooft of the University of Utrecht suggested that the horizon of a black hole, far from being smooth and featureless, is rough and irregular on the microscopic scale. And it's in the lumps and bumps of its Lilliputian landscape that the information which describes the star that gave birth to the black hole is stored.

Shortly after t'Hooft's proposal that the missing information in a black hole might be encoded in its event horizon, Leonard Susskind of Stanford University showed how it might be implemented in string theory. String theory views the fundamental building blocks of everything not as tiny point-like particles but tiny vibrating strings of mass-energy. It's the only framework so far discovered that's compatible with Einstein's relativity theory and his quantum theory of light.

Susskind imagined the event horizon of a black hole as a squirming mass of vibrating strings. Using this picture, in 1997, Andrew Strominger of the University of California at Santa Barbara and Cumrun Vafa of Harvard University were able to predict the exact black hole entropy calculated by Bekenstein.

ABOVE: The action of a black hole, as simulated in computer software. The different colours represent the temperature of the gases that are swirling around the event horizon

Since Hawking radiation is born in the vacuum just a hair's breadth above a black hole's event horizon, it stands to reason that it's influenced by the microscopic undulations of that membrane. Those undulations modulate it in much the same way that the musical notes of a pop song modulate the carrier wave of a radio station. In this way, the information that described the precursor star is carried out into the Universe, imprinted indelibly on the Hawking radiation. No information is lost after all, and one of the most precious laws of physics is left intact.

This proposal for averting the black hole information paradox remains speculative. We still lack the deeper theory that will mesh together Einstein's theory of gravity and quantum theory. But, if correct, it implies something extraordinary. The information to completely describe a star – a 3D body – is perfectly preserved on the horizon of a black hole – a 2D surface. This makes the horizon similar to the holographic image on a credit card. Imagine if a frog carried around with it a hologram of its previous incarnation as

Quasars are the very bright objects at the centre of new galaxies. Their ferocious light comes from matter that's being consumed by a supermassive black hole

NASA/CXC/M WEISS

a tadpole: well, a black hole carries around with it a hologram of its previous incarnation as a star.

FUTURE OBSERVATIONS

Hawking radiation has never been detected in space, and is not likely to be any time soon, because of its weakness for stellar-mass black holes. However, in recent years, physicists have used considerable ingenuity to create analogues of event horizons in Earth-bound laboratories.

"Hawking radiation is not specific to astrophysics," says Germain Rousseaux of CNRS in France, "but is a general prediction that applies equally to both astrophysical black hole horizons and analogue horizons, which have the great advantage to be testable in a laboratory." In 2016 a team that included Rousseaux successfully confirmed the Hawking effect in a water tank ('Observation of Noise Correlated by the Hawking Effect in a Water Tank' by Léo-Paul Euvé *et al*, *Physical Review Letters*, September 2016).

Meanwhile, the quest to actually image the horizon of a black hole in space continues. The problem astronomers face is that stellar-mass black holes in our Milky Way are small and, well, black. Supermassive black holes, though big, are at cosmic distances and so also appear small. However, there is one black hole that's both relatively nearby and relatively large, and that's the black hole at the centre of our Galaxy.

In the next year or so, astronomers hope to image the event horizon of Sagittarius A*, some 26,000 light-years away at the centre of the Milky Way, using an array of cooperating radio telescopes scattered around the globe known as the Event Horizon Telescope. The radio signals recorded at each site are combined on a computer at the MIT Haystack Observatory in Massachusetts to simulate the view through a giant dish the size of the Earth. The bigger the dish and the shorter the observing wavelength – EHT is using a wavelength of 1.3 millimetres – the more it can zoom in on details in the sky.

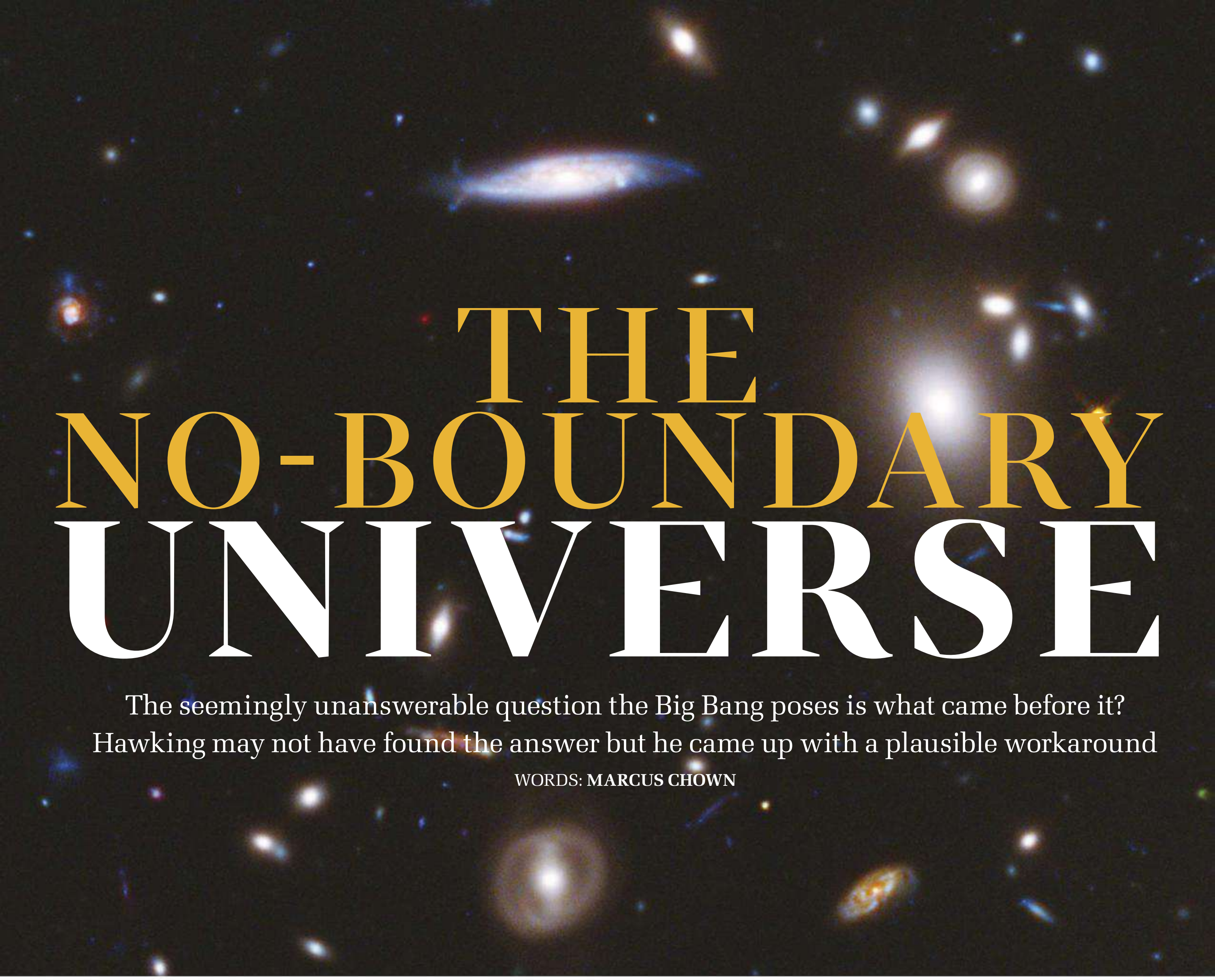
The EHT will test a controversial recent claim by Hawking. Having shocked the world of physics by claiming that black holes are not black but emit Hawking radiation, in 2014, he did it again. This time he claimed that event horizons do not exist, which means that, strictly speaking, neither do black holes!

The collapse of an object such as a star to form a black hole is violently chaotic and, rather than a horizon, all it forms, claimed Hawking, is a boundary of extreme space-time turbulence. Information can leak out through such an apparent horizon. Hawking's conclusion was dramatic. "The absence of event horizons means that there are no black holes – in the sense of regimes from which light can't escape to infinity," he wrote. "There are, however, apparent horizons which persist for a period of time."

Black holes, in other words, are not what we thought they were. So is the horizon around a black hole the point of no return everyone thought it was? Or is it merely an apparent horizon, as Hawking suggested, leaking stuff from inside the hole? The key thing is to observe the horizon and see whether it behaves as predicted by Einstein, or even whether it exists at all. "An image will allow us to test general relativity at the black hole boundary, where it has never been tested before," said Shep Doeleman of the Massachusetts Institute of Technology and leader of the EHT team. "It would symbolise a turning point in our understanding of black holes and gravity."

The EHT will obtain the first image of a black hole event horizon within the next year or so, and it promises to be an iconic image to rival Apollo 8's picture of the Earth rising above the Moon. It's sad to think that Stephen Hawking will not be around to see it.

THE NO-BOUNDARY UNIVERSE



The seemingly unanswerable question the Big Bang poses is what came before it? Hawking may not have found the answer but he came up with a plausible workaround

WORDS: **MARCUS CHOWN**

The Universe has not existed forever – it was born. 13.82 billion years ago all matter, energy, space – and even time – erupted into being in a titanic fireball called the Big Bang. The fireball began expanding and, out of the cooling debris, there eventually congealed the galaxies – great islands of stars of which our Milky Way is one of an estimated two trillion. This, in a nutshell, is the Big Bang theory.

The evidence that the Universe simply popped into existence, like a rabbit out of a hat, is overwhelming. If it wasn't, most scientists would have gladly dismissed it as utterly ridiculous. As it was, they had to be dragged kicking and screaming to the idea of the Big Bang, and it's not hard to see why. Accepting that the Big Bang happened meant having to face the awkward question: what happened *before* the Big Bang?

In recent years, many cosmologists have come to believe that our Big Bang universe is merely one among countless others, continually forming like frothy bubbles in a great ocean of expanding 'inflationary vacuum'. The inflationary vacuum is a weird thing that expands ever faster, spawning ever more Big Bang universes, into the infinite future. And this gave theorists hope. If inflation is never-ending, or eternal, might it not have had a beginning either? Sadly, theorists' hopes have been dashed. It appears that even inflation can't have been going an infinite time. The pesky 'what happened before?' question once again rears its ugly head.

Stephen Hawking alluded to this problem in an anecdote he recounted on the first page of *A Brief*

NASA/HUBBLE SPACE TELESCOPE

History of Time. A well-known scientist – who Hawking says may have been Bertrand Russell – was giving a public lecture about the current picture of the Universe. He described how the Earth orbits around Sun, and the Sun, in turn, orbits around the centre of a vast collection of stars called our Galaxy. At the end of the lecture, a little old lady at the back of the room got up and said: "Professor, what you've been talking about is utter rubbish. Everybody knows the Earth rests on the back of a giant turtle."

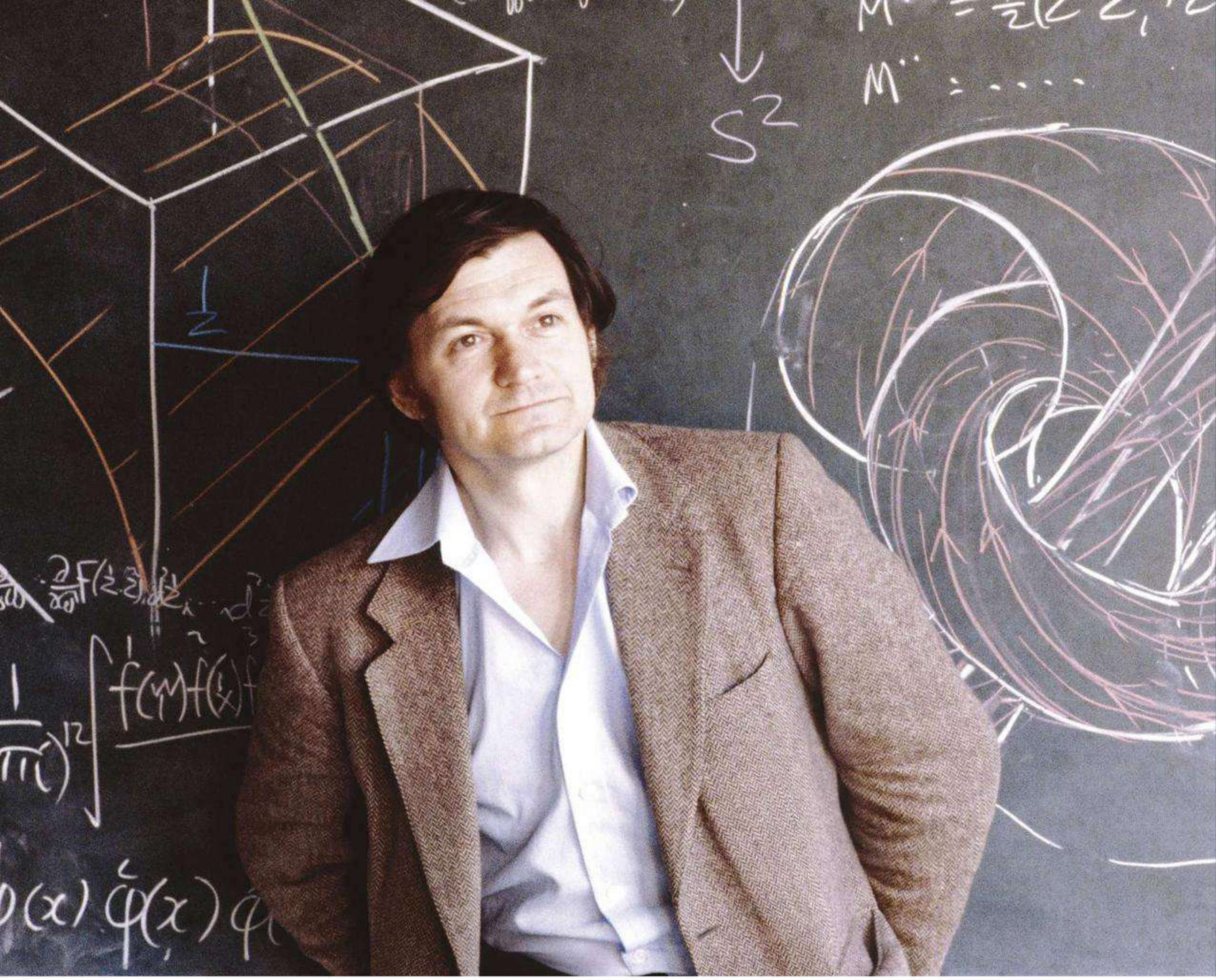
"Okay," said Russell, patiently. "So, what is the turtle standing on?"

"Ah, you're not going to catch me out there, professor!" the insistent old lady replied. "It's turtles all the way down!"

The infinite regress, with endless 'what happened before?' questions, might seem impossible to avoid. But, remarkably, in the early 1980s, Stephen Hawking found a way to do it. At the time, he was working with fellow physicist Jim Hartle of the University of California at Santa Barbara.

Hawking and Hartle were well aware that Einstein's theory of gravity predicted a nonsensical singularity at the beginning of the Universe. How could they not be when it had been Hawking himself, working with Roger Penrose, who had proved such singularity was unavoidable and

"The endless 'what happened before?' questions might seem impossible to avoid"



therefore that the General Theory of Relativity broke down? [See 'Singularities', p50].

The Universe in its earliest moments of the Big Bang was smaller than an atom, and the theory that described the submicroscopic world – hugely successfully – was quantum theory. Most physicists therefore suspected that if we were ever to understand the birth of the Universe and where it came from, we'd need to find a quantum theory of gravity.

In quantum theory, everything that can be known about an entity such as an atom is encapsulated in a mathematical expression known as a wave function. Hawking and Hartle therefore attempted to write down a wave function that represented the entire Universe.

Very quickly, they made a striking discovery. Einstein's theory of gravity can be reformulated so that, instead of describing three dimensions of space and one of time, it has three dimensions of space and one of 'imaginary time'. Imaginary time is a weird mathematical concept, but the key thing about it is that it behaves just like space. Hawking and Hartle were able to demonstrate that the wave function of the Universe, which today exists in space and time, could have started out in space alone.

The significance of this is that the Big Bang singularity predicted by Einstein's theory exists only in time, and removing time automatically removes the singularity. The theory doesn't blow up like Einstein's theory of gravity. But, most crucially, asking 'What happened before the big bang?' becomes like asking 'What lies beyond the North Pole?', which is of course meaningless. With this so-called no-boundary condition, Hawking and Hartle had sidestepped the 'What happened before?' question; there *was* no before, because a before exists only in time.

In other words, asking what the turtle was standing on was simply not a scientifically sensible question to ask.

ABOVE: Roger Penrose shared the 1988 Wolf Prize for Physics with Stephen Hawking for their work on singularities and the role they played in the beginning of the Universe

RIGHT: About 13.8 billion years ago a singularity kickstarted the Universe, which, in its initial moments of expansion, was no bigger than an atom

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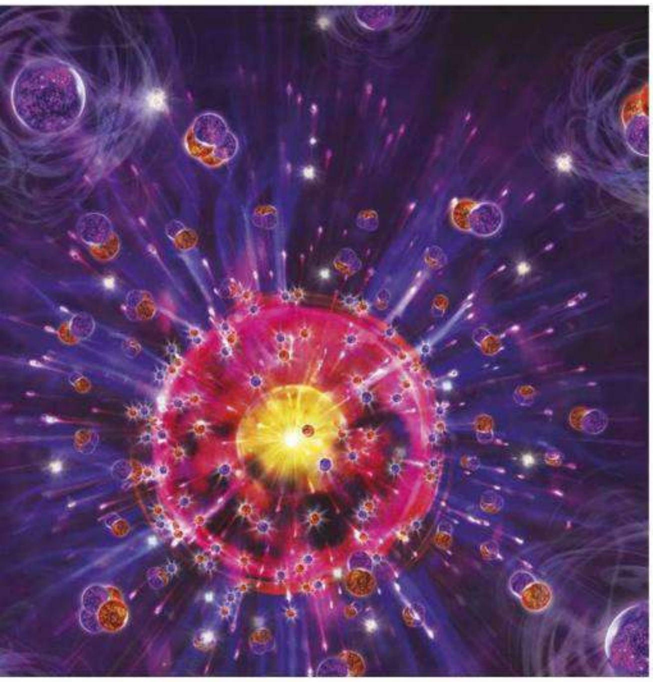
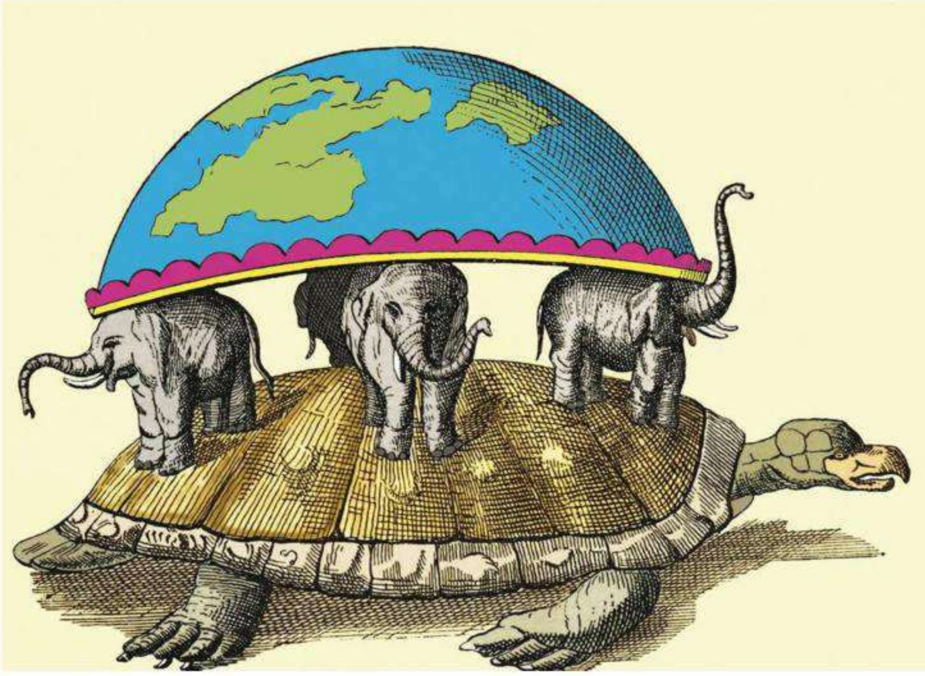
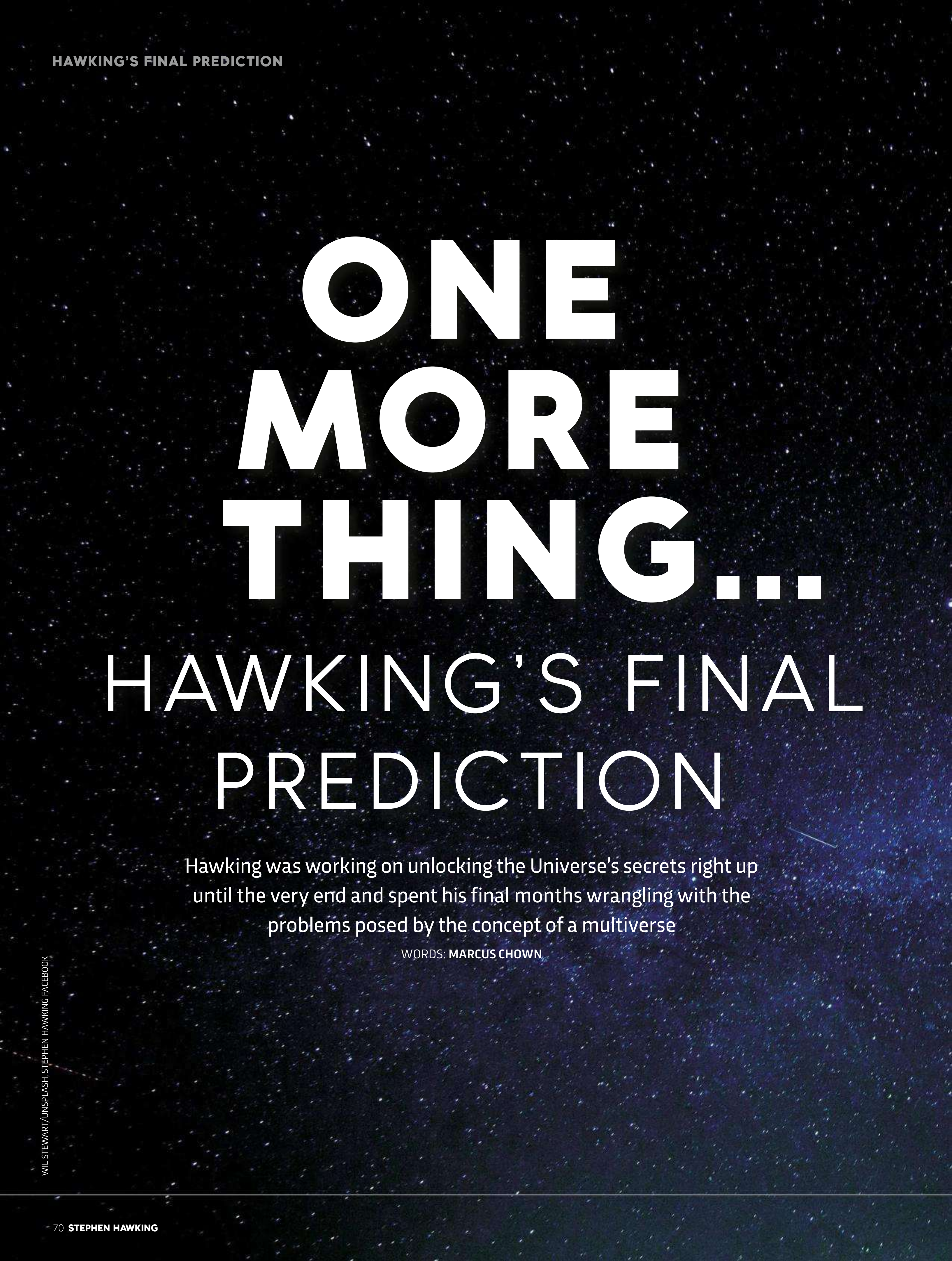
LEFT: A wave function describes the quantum state of a system of one or more particles. Stephen Hawking and Jim Hartle attempted to come up with the a wave function for the Universe

BELOW: The inevitable question the 'turtles all the way down' idea raises is what's holding the turtle(s) up? The infinite regression this leads to is akin to the question of what came before the Big Bang?

"The Universe in its earliest moments of the Big Bang was smaller than an atom, and the theory that described it was quantum theory"







ONE MORE THING...

HAWKING'S FINAL PREDICTION

Hawking was working on unlocking the Universe's secrets right up until the very end and spent his final months wrangling with the problems posed by the concept of a multiverse

WORDS: **MARCUS CHOWN**

WIL STEWART/UNSPLASH, STEPHEN HAWKING FACEBOOK

Einstein's theory of gravity breaks down at the singularity found at the heart of a black hole and in the Big Bang, so we know it's an approximation of a deeper theory that may explain everything. The hope among physicists is that this 'theory of everything' (TOE) will unite the theory of the big (Einstein's theory of gravity) with the theory of the small (quantum theory). In 1974, Stephen Hawking's genius was to find a place – the event horizon surrounding a black hole – where, despite lacking the TOE, he could nevertheless predict something about the world: Hawking radiation. In the last year of his life, he claimed to have found another location where it's possible to make a sensible prediction: the Big Bang itself.

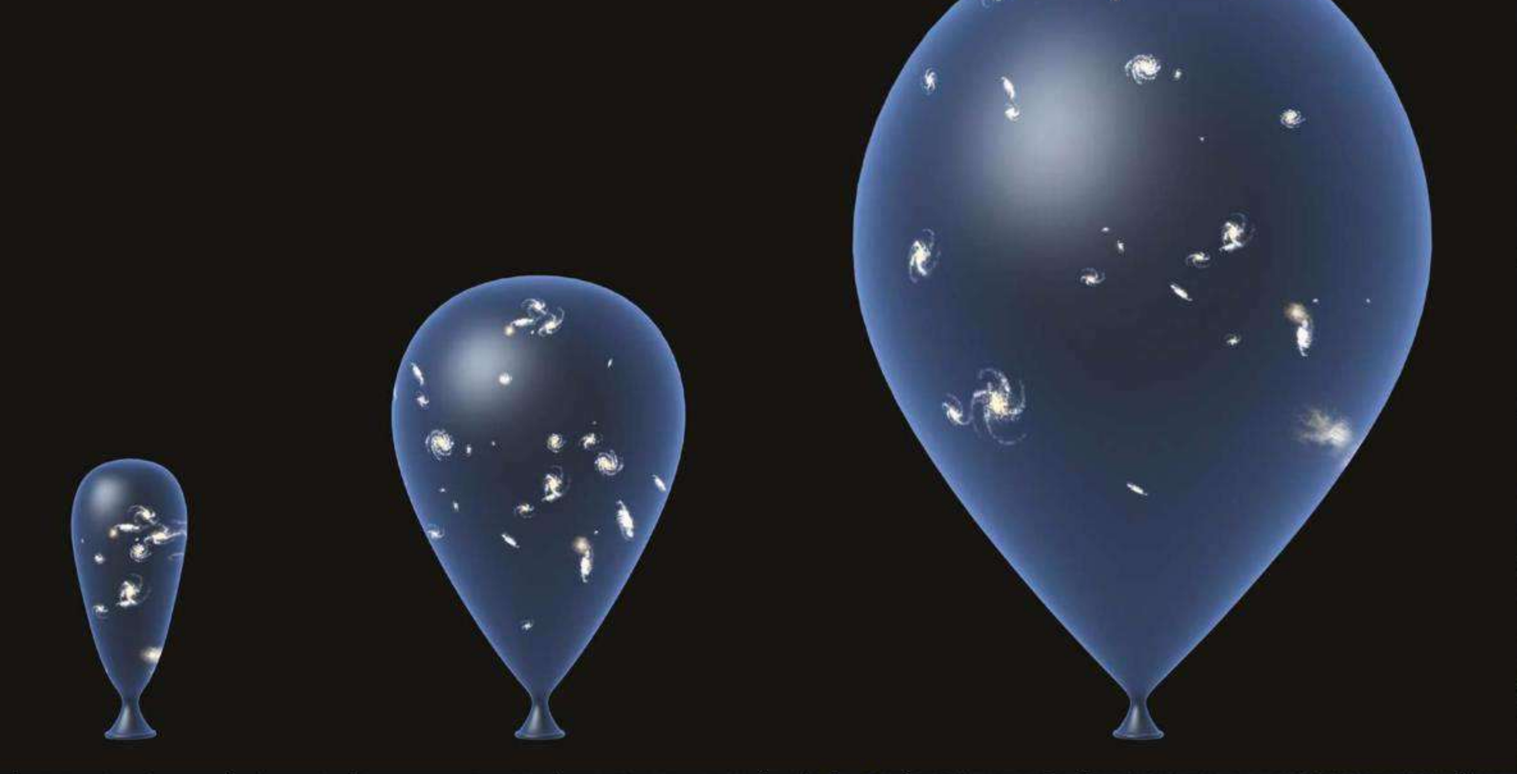
Hawking and his colleague, Thomas Hertog of the University of Leuven in Belgium, initially aimed to put Hawking and Hartle's no-boundary Universe concept of the early 1980s on a firmer theoretical footing [See 'No-boundary Universe', p66]. To their delight, they discovered that their model predicted that our Universe came into existence with a phase of inflation, the super-fast cosmic expansion believed to have occurred in the Universe's first split-second and which is a key component of today's standard Big Bang model.

> "In the last year of his life, Hawking claimed to have found another location where it's possible to make a sensible prediction: the Big Bang itself"

UNIFORM TEMPERATURE

Inflation explains why today's Universe has the same temperature everywhere even though, in the Big Bang, far-flung places were not in contact with each other and so couldn't have exchanged heat to equalise their temperatures. A cosmos that expanded faster than expected early on in its life could have started out

ABOVE: Stephen Hawking's collaboration with Thomas Hertog, of Belgium's University of Leuven, resulted in a more manageable concept of the multiverse



ABOVE: The Universe's expansion is analogous to an inflating balloon – galaxies recede from each other as if they are situated on the fabric of the balloon as it's gradually inflated

smaller – allowing the exchange of heat – while still reaching its current size in the 13.82-billion-year age of the Universe.

Inflation was driven by a high-energy state of the vacuum with repulsive gravity, which caused it to expand and grow. The more of it there was, the greater the cosmic repulsion and the faster it expanded. But the inflationary vacuum was a quantum thing, which meant it was fundamentally unpredictable and decayed at random places into normal, everyday vacuum. Think of bubbles forming in an ever-expanding ocean. Inside each bubble, the energy of the inflationary vacuum has to go somewhere. And in the case of the very earliest moments of our Universe's existence it went into creating matter and heating it to a ferociously high-temperature. It created a big bang. In this scenario, big bangs go off constantly like stuttering firecrackers all over the inflationary vacuum. We live inside one such big bang bubble.

The inflationary vacuum, however, is created faster than it's eaten way, so inflation, once started, never finishes. It's eternal. This creates an ensemble, or multiverse, of universes.

The only framework so far that unites quantum theory and relativity is string theory, which views the fundamental building blocks of matter as ultra-tiny vibrating strings of mass-energy. Hopes that string theory might point to a TOE were dealt a blow when it was discovered there was not one but at least 10,500 string vacua, each with different fundamental particles and fundamental forces.

Hawking and Hertog, along with others, equate the string vacua with the multiple universes of eternal inflation. However, this makes cosmology mind-bogglingly complex and practically untestable. "We therefore set out to tame the Multiverse," says Hertog.

THOSE LEFT BEHIND

To do this, Hawking and Hertog noted that Einstein's theory of gravity in four dimensions of space-time is conjectured to be equivalent to string theory in three dimensions. Using this 'holographic duality', they were able to transform their problem into something more tractable. They discovered that this constraint culled the wilder universes, leaving behind only those that are similar to ours, greatly reducing the number of universes in the Multiverse.

Until now, theorists have faced the problem of explaining what we see in our Universe statistically – that is, by showing that we live in one of the most common universes of the Multiverse, the one with the most common mass for the electron, strength of the gravity and so on. This is a daunting, if not impossible, task, given the large number of universes in the Multiverse. But Hawking and Hertog say that this reasoning may be much easier with their cut-down Multiverse. "We may after all be able to explain our Universe despite not being able to observe the other regions of the Multiverse," says Hertog. "With our paper we take a step towards turning the no-boundary model of the Big Bang into a predictive framework for cosmology."

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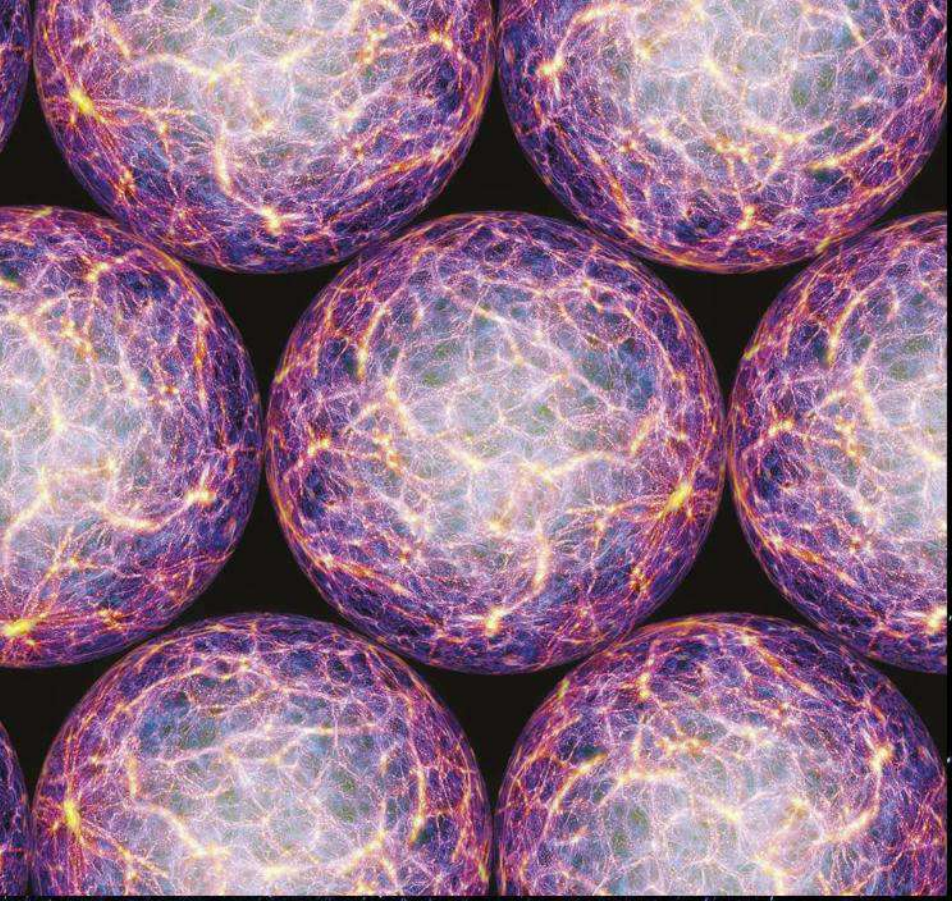

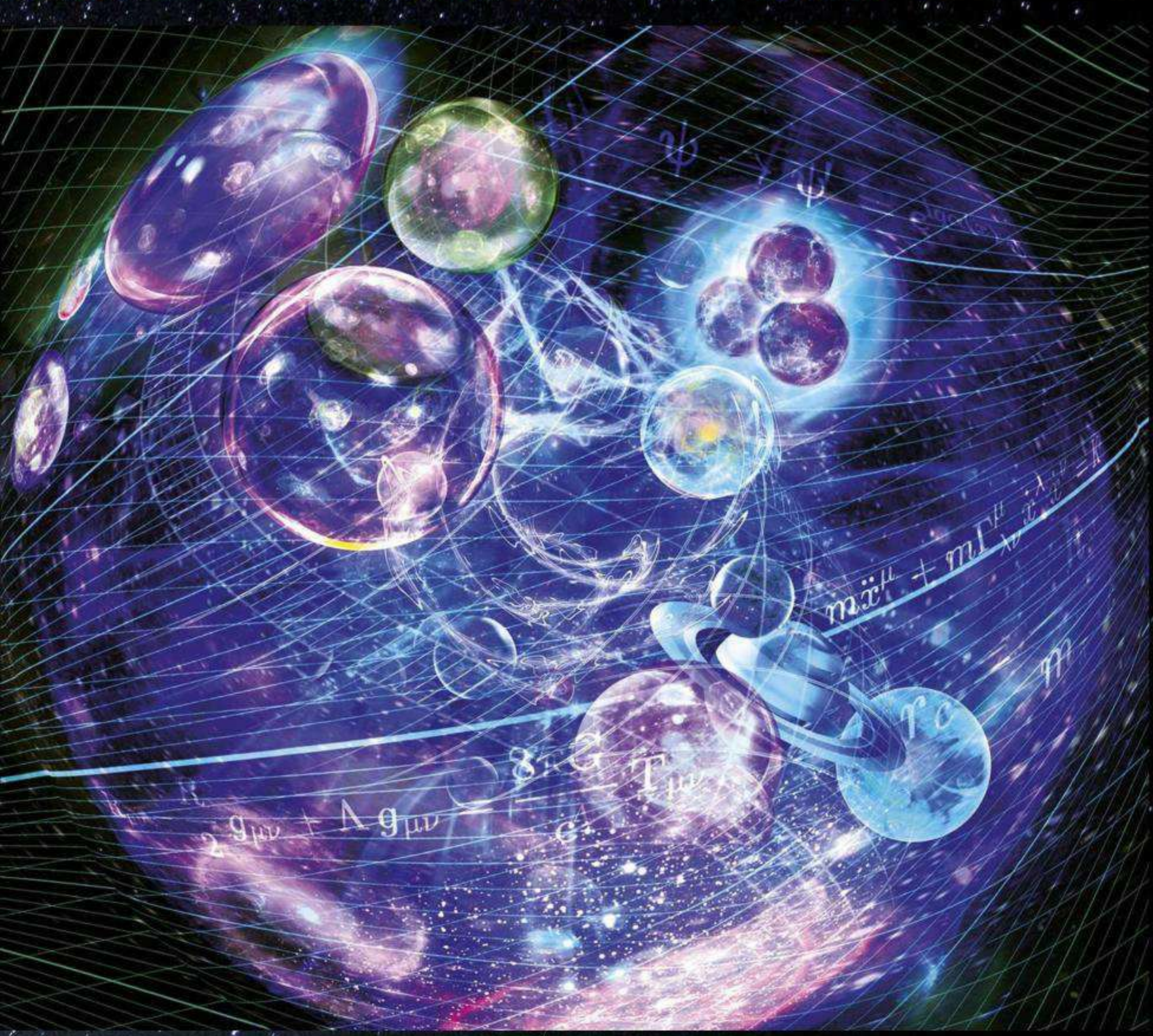

ABOVE LEFT: Inflationary expansion is faster than the speed of light, and could have formed bubble universes that would be completely isolated from each other

ABOVE: Bubble universes may have formed in the early universe, where false vacuums created a repulsive force that caused an incredibly rapid expansion

LEFT: The theory of everything remains hypothetical but attempts to unify quantum field theory and general relativity

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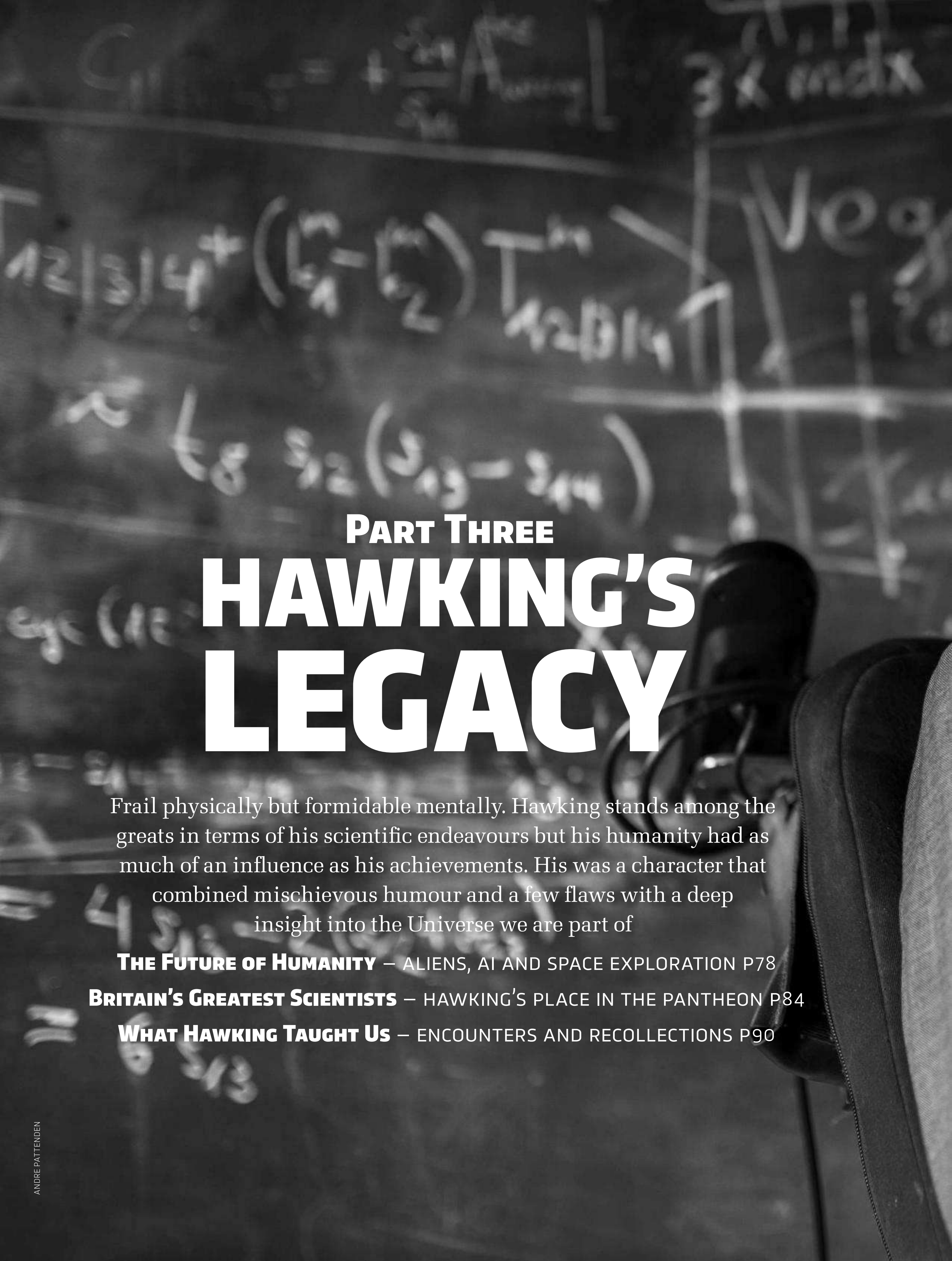


ANDRE PATTENDEN

Part Three

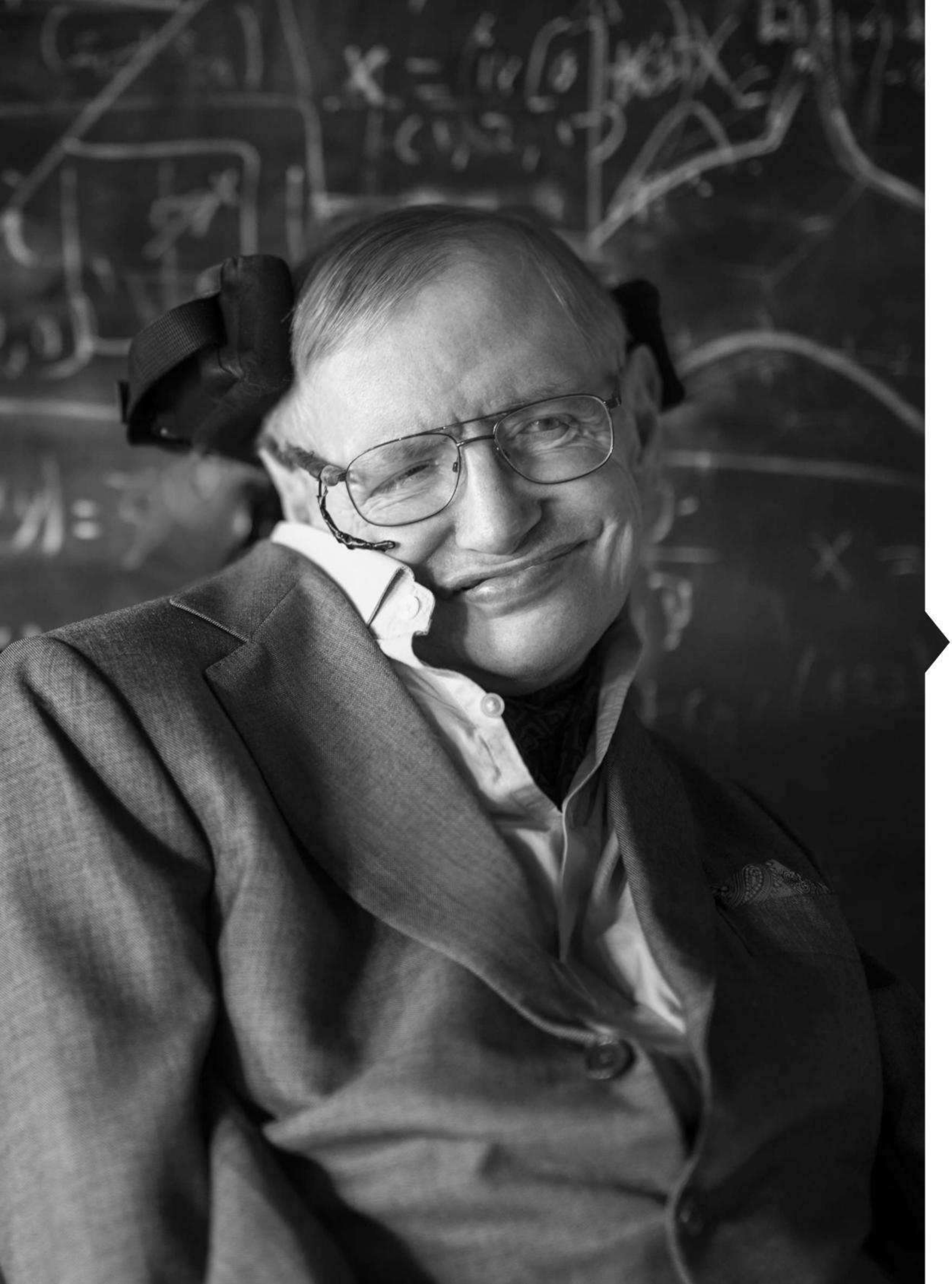
HAWKING'S LEGACY

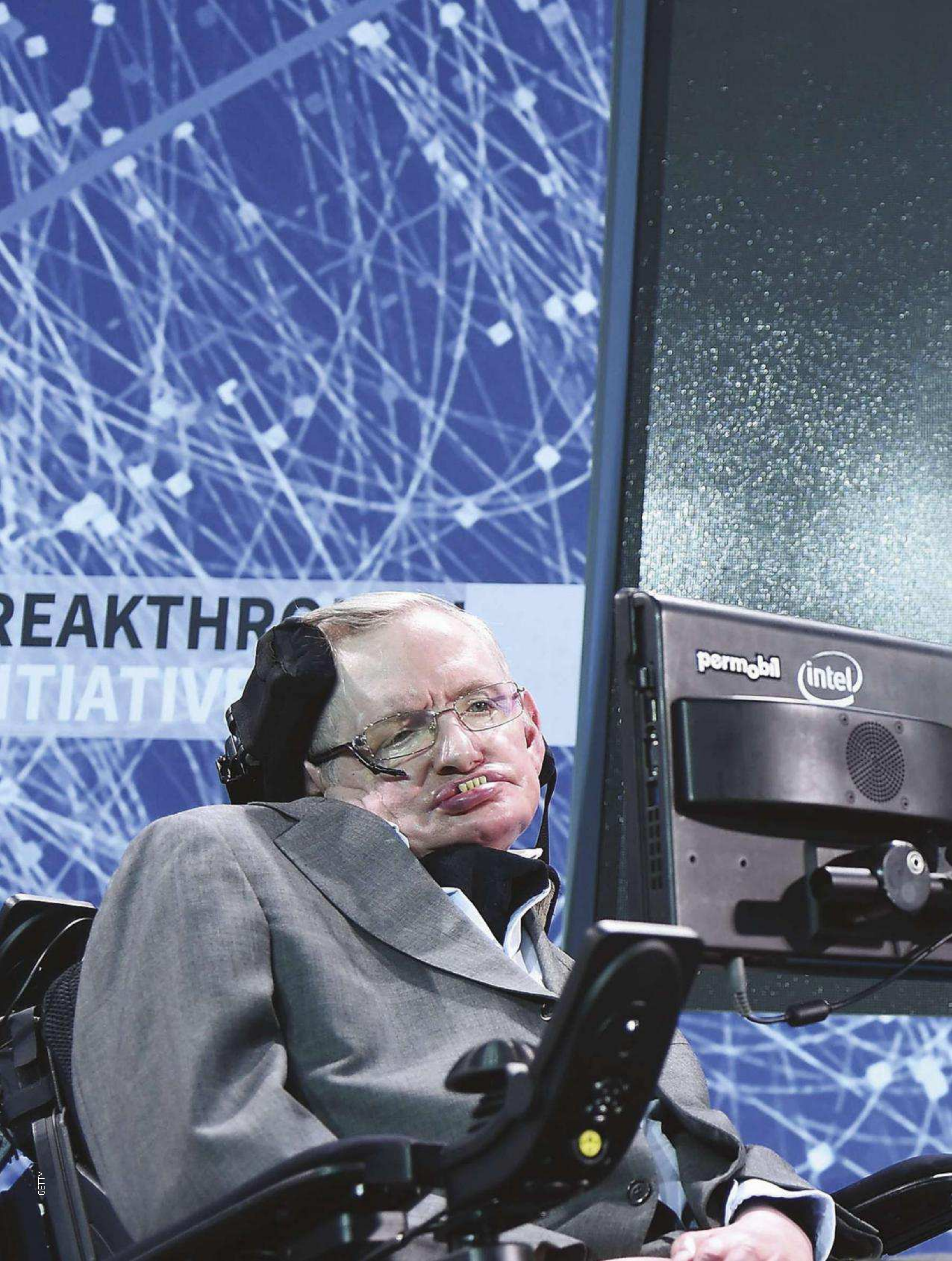
Frail physically but formidable mentally. Hawking stands among the greats in terms of his scientific endeavours but his humanity had as much of an influence as his achievements. His was a character that combined mischievous humour and a few flaws with a deep insight into the Universe we are part of

The Future of Humanity – ALIENS, AI AND SPACE EXPLORATION P78

Britain's Greatest Scientists – HAWKING'S PLACE IN THE PANTHEON P84

What Hawking Taught Us – ENCOUNTERS AND RECOLLECTIONS P90





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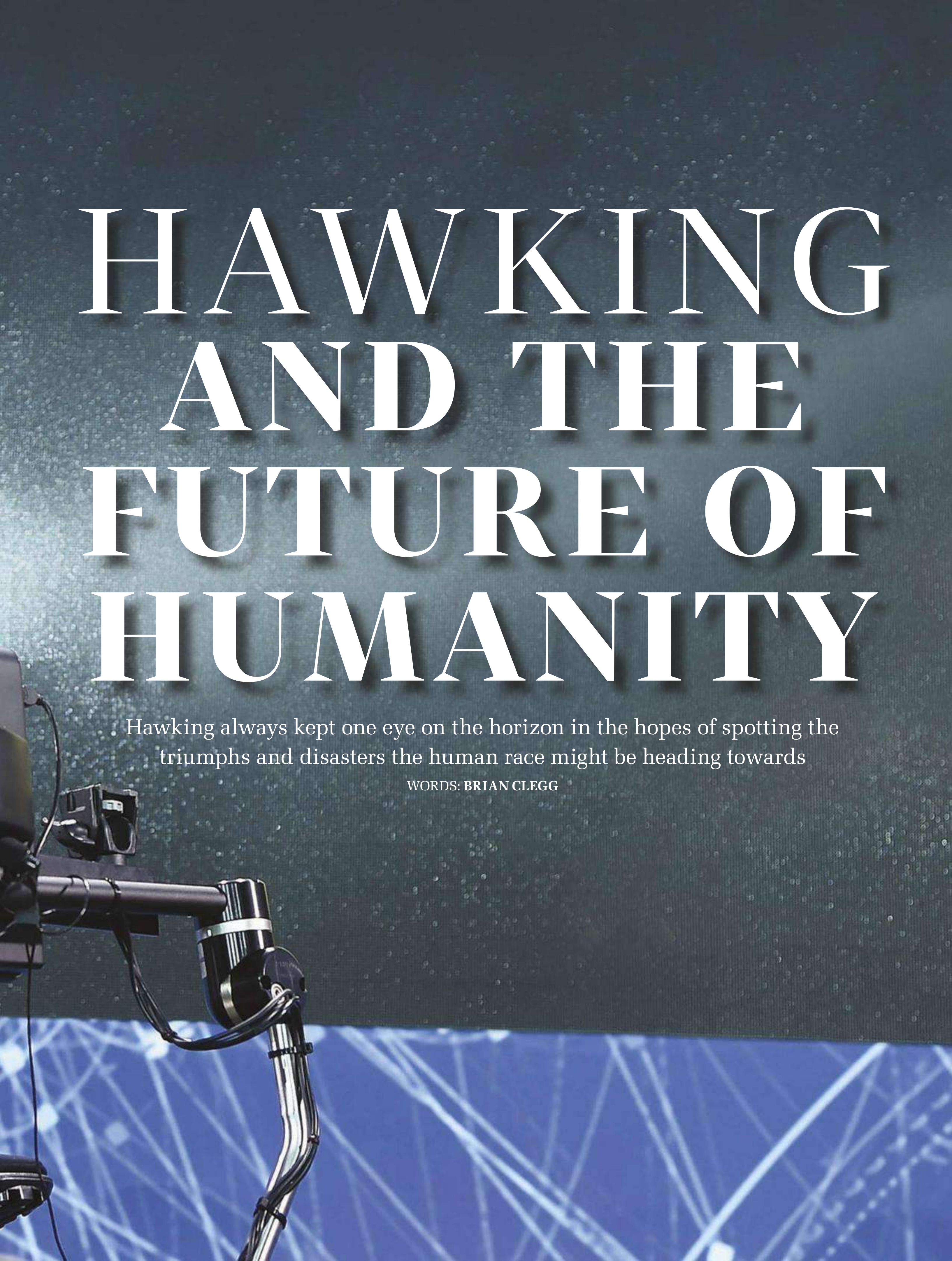
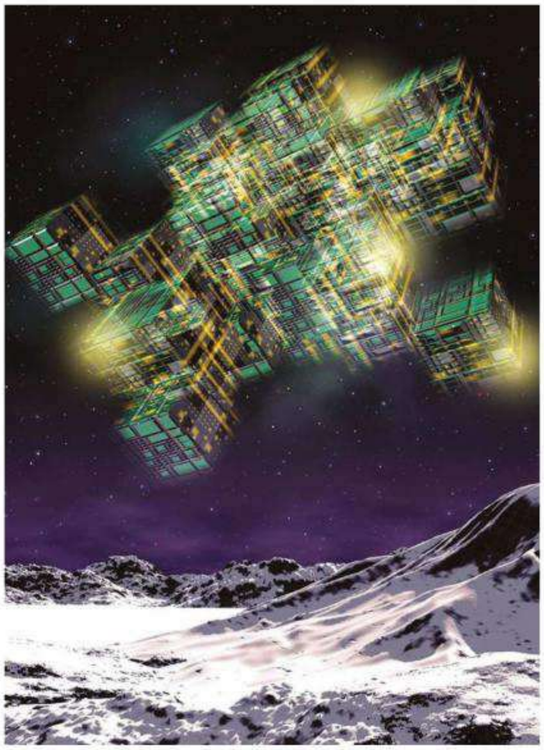


HAWKING AND THE FUTURE OF HUMANITY

Hawking always kept one eye on the horizon in the hopes of spotting the triumphs and disasters the human race might be heading towards

WORDS: **BRIAN CLEGG**



RIGHT: Von Neumann probes could explore deep space by travelling to other worlds, mining materials to replicate themselves and then dispatching their progeny off to explore further

BELOW: SETI's Seth Shostak thinks concerns regarding alerting extraterrestrial life to our presence are largely academic given the signals we've been broadcasting into space for generations

BOTTOM: Google's AI program AlphaGo beat Lee Se-dol, a top human player from South Korea, at the strategy game Go in March 2016

With the possible exception of Albert Einstein, no other physicist in history has had a public persona to rival Stephen Hawking's. And in his later years, he made full use of this position in the public eye to share his thoughts on the threats and opportunities facing humanity.

Stories emerged in the press of Hawking's views on risks from aliens, or from our creation of artificial intelligence, out of control computer viruses and global warming. His future gazing wasn't limited to the negative – see, for instance, his involvement in the Breakthrough Initiatives programme, with its focus on reaching the stars. But it was the warnings that were hardest to ignore.

When it comes to getting a better picture of Hawking's views, we must always bear in mind his wicked sense of humour. His warnings may have concerned serious issues, but it's hard to believe that there wasn't a degree of teasing or mischief-making, particularly when it proved easy to get an excited response from the tabloid press. Yet, typically of Hawking, his arguments were always interesting.

THE ALIENS ARE COMING

The starting point for examining any risk that aliens may pose has to be assuming the existence of intelligent extraterrestrial life. As Hawking pointed out in a 1996 lecture, life may have emerged as early as 500 million years into the 4.5-billion-year existence of the Earth. This could indicate that it's easy for life to start. But all known terrestrial life appears to be descended from the same source, suggesting that our early start may be a rare occurrence. Hawking noted that the probability of evolving intelligent life certainly appeared low. He also considered that many successful lifeforms could be wiped out by bombardments of asteroids and comets, or could self-destruct, before they developed the technology to leave their planet.

Whether intelligent life is rare or common, as Hawking noted, "According to the theory of relativity, nothing can travel faster than light. So the round trip to the nearest star would take at least eight years, and to the centre of the galaxy, about 100,000 years. In science fiction, they overcome this difficulty by space warps or travel through extra dimensions. But I don't think these will ever be possible." A much more likely mechanism for alien interstellar exploration, he suggested, would be some form of self-replicating mechanical life.

Such devices, known as von Neumann probes after Hungarian American physicist John von Neumann who dreamt them up in the 1940s, could survive lengthy journeys. If the Universe were teeming with life, it would seem likely that there would be plenty of such probes in action and that we would have been visited many times. Yet there is no evidence of this.

In his lecture, Hawking argued that it was worth supporting initiatives that searched for extraterrestrial signals, one of the themes of Breakthrough Initiatives. However, he also thought that replying is probably best left until we're further developed. As he put it: "Meeting a more advanced civilisation, at our present stage, might be a bit like the original inhabitants of America meeting Columbus. I don't think they were better off for it."

Despite any concerns, Hawking was happy to be associated with the Breakthrough Initiatives programme, which includes a competition to design a message to be beamed into the stars. And as Seth Shostak of the SETI Institute commented in *The Guardian* in 2016, the notion that we could hide by not sending a message to aliens is unrealistic: "Since the Second World War, we've been broadcasting television, high-frequency radio and, most conspicuously, radar into the heavens. Little of this is done with the intention of either entertaining or notifying aliens, but is simply an inevitable leakage of radio transmissions into space."

Such broadcasts would be very weak when they reached the stars. But, as Shostak pointed out, the technical challenges of travelling across many light-years of space are far greater than those of picking up and decoding a weak radio or TV signal: "And since we've been busy for a lifetime filling the seas of space with bottled messages marking our existence and position, it's a bit silly to fret about new bottles."

TOO CLEVER BY FAR

More likely threats to human existence are those we produce ourselves. Artificial intelligence (AI) has many potential benefits, but it's easy to imagine it getting out of control. As Hawking pointed out in a 2014 BBC interview, sophisticated AI software is capable of learning and evolving at a far faster rate than humans. We've seen this on a trivial level when AIs have beaten masters at the game of Go and taken on video games, learning how to better the highest human scores, sometimes by cheating.

"Humans who are limited by slow biological evolution," Hawking observed, "couldn't compete, and would be superseded." In 2015, Hawking

THE AI THREAT

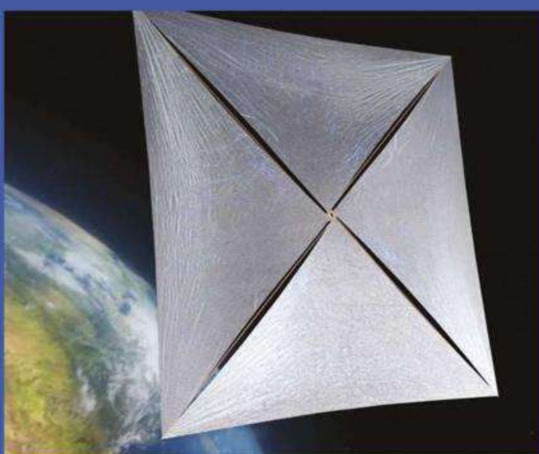
What happens when cars and toasters become self aware?

Few individuals knew better than Stephen Hawking the benefits of information technology, but he also highlighted the dangers posed by out-of-control artificial intelligence (AI). The potential arises when we give computer software the ability to make decisions that can have direct impact on our lives.

Broadly, the risk from AI can be divided into three types. The most likely is simple error. An AI could be better at performing a particular task than a human, but still capable of making mistakes. Here the threat is arguably perception. Currently, over a million people a year are killed on the roads worldwide. Imagine all cars were driverless, controlled by AIs, and cut this death toll in half. Would this be perceived as half a million lives saved, or AIs killing half a million people? The first pedestrian death caused by a driverless car occurred in March 2018.

The second concern is that AI systems could be subverted by hackers, while thirdly, AIs could gain sufficient ability for independent thought and decide that their wishes overrode those of humanity. This is the threat most highlighted by Hawking.

At the mild end of this risk is the possibility that an AI simply loses interest, choosing perhaps to watch movies all day rather than do its job. The nightmare scenario involves an AI that decides humanity gets in the way of fulfilling its goals. With access to our life support systems, from food distribution and power generation to defence systems, such a rogue AI could wipe out the majority of human life to follow its own ends. This suggestion may seem like science fiction, but Hawking argued it's only by thinking through these possibilities that we can ensure we're safe.



ABOVE: Hawking and the Russian billionaire Yuri Milner form two thirds of the board of the Breakthrough Initiatives programme

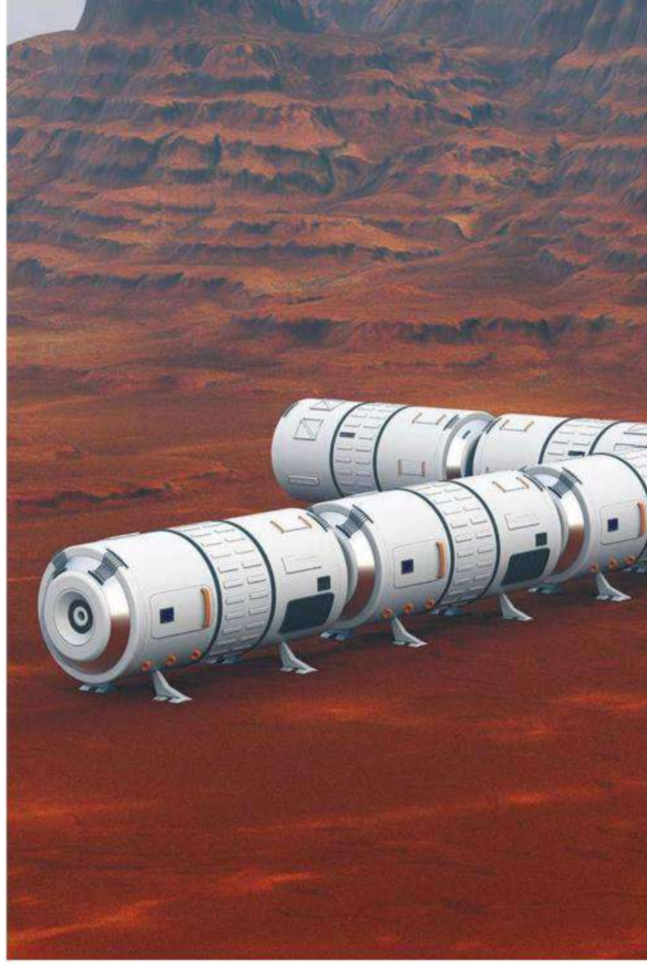
LEFT: Breakthrough Starshot is an initiative that intends to send a fleet of tiny spacecraft on an interstellar journey using solar sails and lasers

BREAKTHROUGH INITIATIVES

Plans are afoot to find, contact and maybe even reach civilisations beyond our solar system

Despite Stephen Hawking's concerns that alerting aliens to our existence could be potentially hazardous, he was a strong supporter of Breakthrough Initiatives. The programme consists of Breakthrough Listen – following up the old SETI (Search for Extra Terrestrial Intelligence) initiative in hunting for electromagnetic signals from alien sources; Breakthrough Message – a competition to design a message from Earth to other civilisations; Breakthrough Watch – contributing to the search for planets around other stars; and Breakthrough Starshot – a research project to send small unmanned probes towards the stars at up to 20 per cent of the speed of light (0.2 c).

Hawking was actively involved in Breakthrough Starshot, joining Mark Zuckerberg of Facebook and Yuri Milner of internet company DST Global on the project board. Starshot's goal is to produce thousands of tiny nanocraft or 'Sprites' – wafers that weigh just a few grams but are able to carry cameras, thrusters, power storage and communication equipment, and are attached to a solar sail. These would be launched into a high orbit, then accelerated to the desired speed using a high-powered bank of lasers. If 0.2 c could be achieved, these nanocraft could reach our nearest stellar neighbour, Alpha Centauri in about 20 years. Though many would be lost along the way from impacts with dust and cosmic rays, enough might survive to make this the start of interstellar exploration.



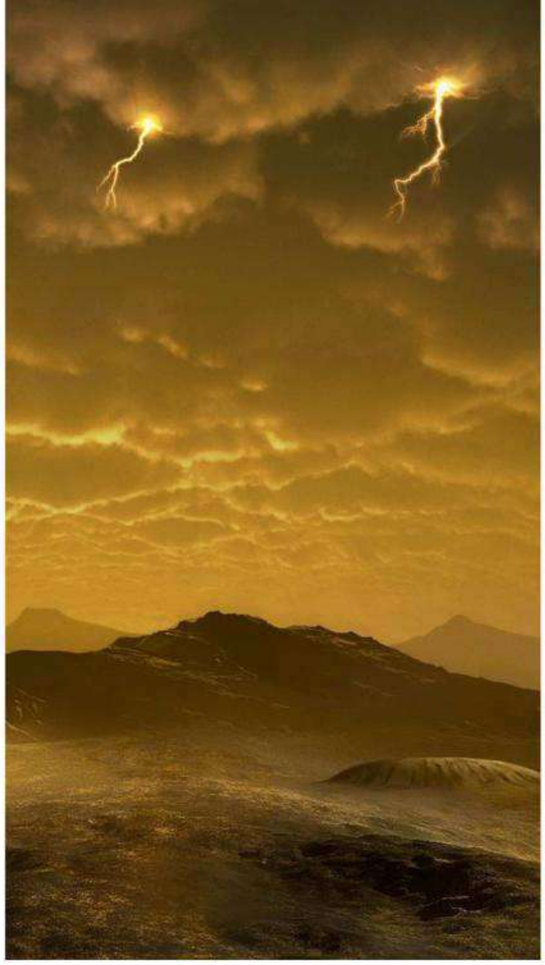
joined Elon Musk and AI experts in signing an open letter calling for greater efforts to be made to prepare for the pitfalls of creating artificial intelligence.

The parallel Hawking draws with evolution is significant. Biological evolution enabled intelligent life to develop over many millennia. But AI can evolve much faster. Hawking said, "it would take off on its own and re-design itself at an ever-increasing rate."

Science fiction has given us the image of attack by evil machines, but Hawking suggests: "The real risk with AI isn't malice but competence. A super-intelligent AI will be extremely good at accomplishing its goals, and if those goals aren't aligned with ours, we're in trouble." He also warned of the dangers of computer viruses and the use of the internet as a 'command centre' for crime and terrorism.

WHERE DO WE GO FROM HERE?

Hawking was concerned with the risks we face, both human and cosmic, that could render the Earth uninhabitable. He pointed out that, like the dinosaurs, we could find our environment so disrupted by a major asteroid impact that life on Earth becomes unsustainable. In questions after the 2016 BBC Reith Lectures, he underlined the dangers of nuclear war, climate change and genetically engineered viruses. A year later, he told the BBC that "We are close to the tipping



FAR LEFT: In the face of potential global nuclear or climate disaster, establishing off-world colonies could be key to ensuring the long-term survival of the human race

LEFT: If climate change rendered Earth as inhospitable as Venus – with scorching hot temperatures and sulphuric acid rain, humanity could only continue by taking to the stars

BELOW: Another asteroid strike, similar to the one that wiped out the dinosaurs, could have the same result for humans. Without defences, human settlements on other planets could be the only way to avoid annihilation

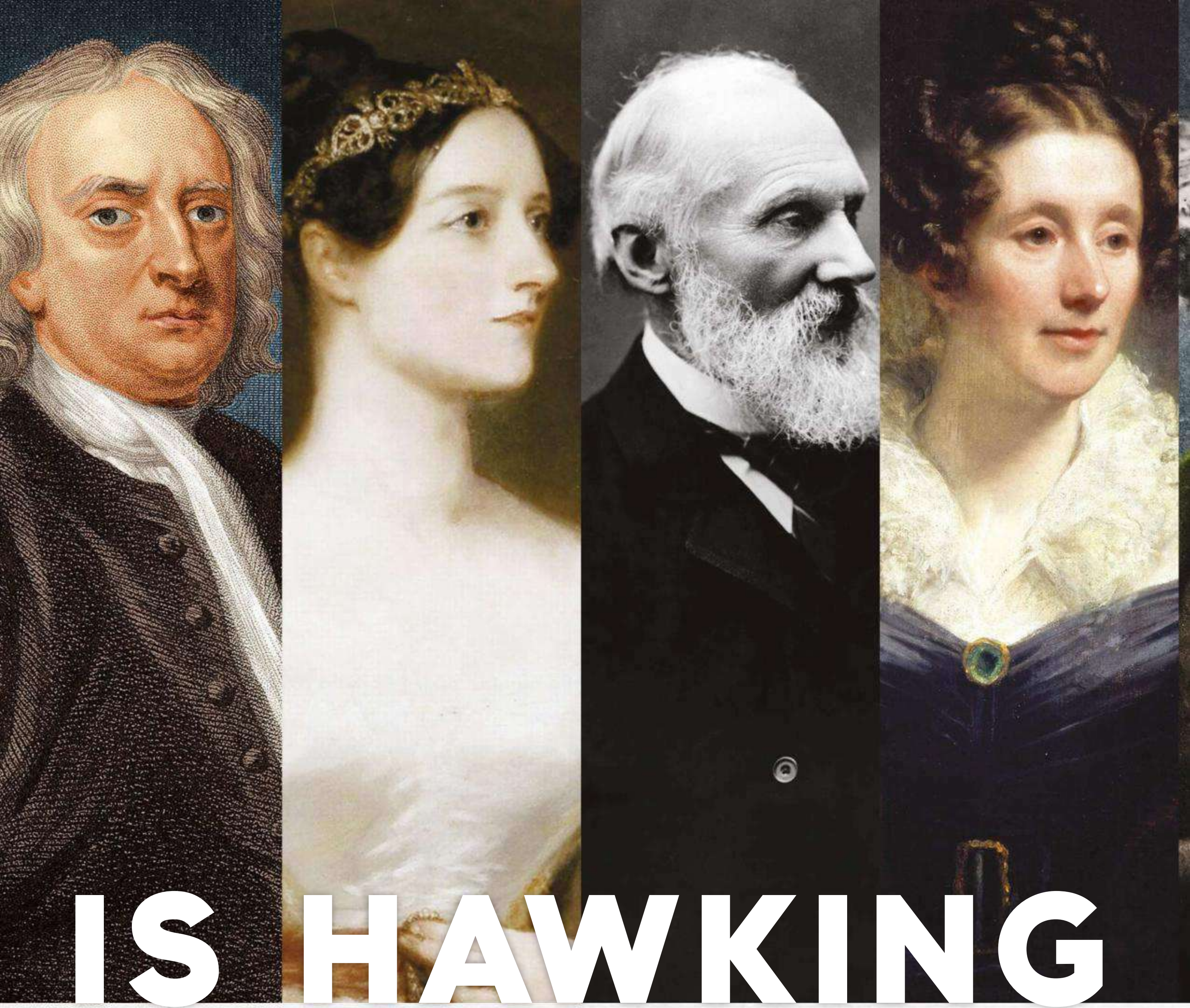
point where global warming becomes irreversible. Trump's action [in withdrawing from the Paris climate agreement] could push the Earth over the brink, to become like Venus, with a temperature of 250°C, and raining sulphuric acid."

A driver for Hawking's enthusiasm for projects such as Breakthrough Initiatives is the need to establish human colonies off Earth before such destruction occurs. In a 2016 interview he set a timescale, saying "Although the chance of a disaster to planet Earth in a given year may be quite low, it adds up over time, and becomes a near certainty in the next 1,000 or 10,000 years. By that time we should have spread out into space, and to other stars, so a disaster on Earth would not mean the end of the human race."

By 2017, Hawking had shortened the deadline, suggesting in the BBC documentary *The Search For A New Earth* that we needed to set up colonies sooner. "We can, and must, use our curiosity and intelligence to look to the stars… for humans to survive, I believe we must have the preparations in place within 100 years."

It might seem that Hawking was pessimistic about our future. But it would be more realistic to portray him as an optimist who saw that, with the right use of science and technology, we could overcome the challenges of the future that would otherwise bring an end to human existence. Hawking's message for humanity, despite those warnings, was one of hope.

GETTY X4, BREAKTHROUGH INITIATIVES



IS HAWKING BRITAIN'S GREATEST SCIENTIST?

Newton, Somerville, Faraday, Darwin, Lovelace, Kelvin, Maxwell, Jeans...
How do the biggest names in British science compare to Hawking?

WORDS: **CHARLOTTE SLEIGH**

GETTY X7, ALAMY

By the time of his death in 1727, Newton was already a megastar and a hero in his home country. Alexander Pope composed an epitaph in his honour:

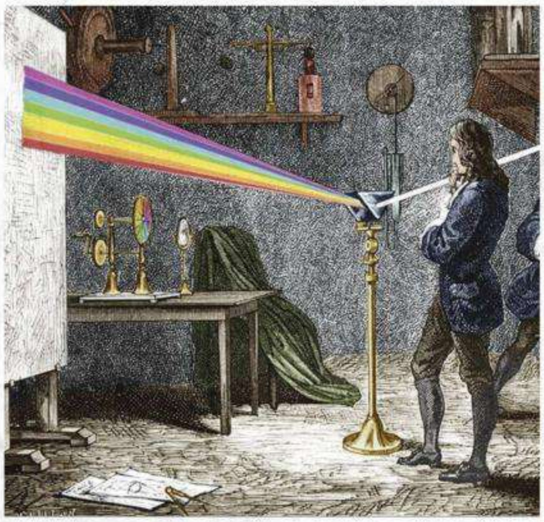
Nature and Nature's Laws lay hid in Night:
God said, "Let Newton be!" and all was light.

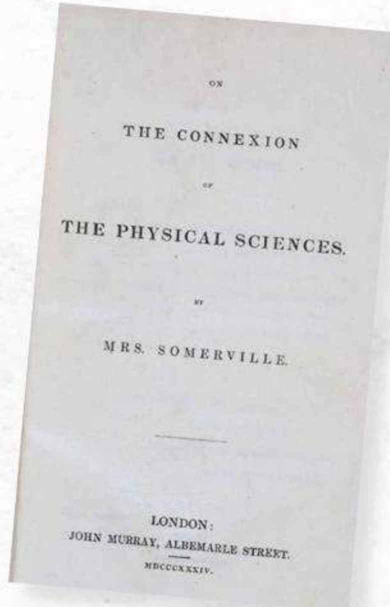
It was supposed to go on his monument at Westminster Abbey, but the authorities wouldn't permit it – raising him to divine status was a step too far.

Less than a week after Stephen Hawking's death, it was announced that his remains would be placed alongside Newton – a decision that was greeted with universal approval. Yet compared with politicians and artists, only a tiny handful of scientists is interred at the Abbey. Why, as a society, are we less comfortable with celebrating our scientists?

Is it, perhaps, that immediately after death feels too soon to decide whether their reputation will last? Should a scientist have found public fame in order to be commemorated? Or should honour after death be compensation for an unrecognised career, as in the case of women? Is hero-making, perhaps, more of an object-lesson for the living than a judgement upon the past?

With such questions in mind, let's see how some past great British scientists measure up against Professor Stephen Hawking...




ON

THE CONNEXION

OF

THE PHYSICAL SCIENCES.

BY

MRS. SOMERVILLE.

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
MDCCCXXXIV.

ISAAC NEWTON
1643-1727

Alchemist, natural philosopher, Master of the Royal Mint

FAMOUS THEN FOR: OPTICS
FAMOUS NOW FOR: GRAVITY

Hawking's reputation has been consciously made within the mould of Sir Isaac Newton, Britain's first bona fide scientific superstar. And just as it was often joked that almost no-one succeeded in reading Hawking's *A Brief History of Time* all the way through, so Newton's reputation was based on the testimony of a very small number of readers. He had thought to write at least part of the *Philosophiae Naturalis Principia Mathematica* "in a popular method, that it might be read by many", but then changed his mind. Voltaire sweated to make sense of it as effortlessly as his compatriot, the physicist Émilie du Châtelet had. He despaired: "[Newton] has found some truths, but he has… replaced them at the bottom of an abyss." Within his own lifetime, Newton was actually better known for his book on optics than he was for the gravitational theory now associated with him. After his death, Newton's reputation was quickly channelled into religious sermonising that bore little resemblance to his real faith, which was as strongly held as it was bizarre and heretical, just as Hawking has been made fodder for a number of 'thoughts for the day'.

MARY SOMERVILLE
1780-1872

Natural philosopher and polymath

FAMOUS THEN FOR: COMBINING PHYSICS AND ASTRONOMY
FAMOUS NOW FOR: NOT MUCH

Through her connections and hard work the young Scot Mary Somerville, née Fairfax, assembled for herself a serious education in mathematics. In the midst of family life, she established a polymathic career, beginning with a report of her own observations on the magnetising power of sunlight. Again, the link with Hawking comes via popularisation; Somerville translated and condensed Pierre-Simon Laplace's five-volume treatise *Traité de Mécanique Celeste*, a heavyweight work combining Newton's theory of gravity with the latest in astronomy. A book of her own devising followed in 1834, and also became a bestseller. It bridged several fields of science with clear writing for all and maths for those who could follow it. *The Oxford Dictionary of National Biography* churlishly notes that Somerville "was not among those 19th-century women who contributed to original work in science." The qualification is unjust. It was hugely difficult for a woman to do experimental work. Moreover, writing and translation were not a passive pursuit; through discussion and elaboration, they too were an active work of science-making. Somerville was criticised in her day for being both too populist and not populist enough. There was no winning for her.

GETTY X5, ALAMY X3

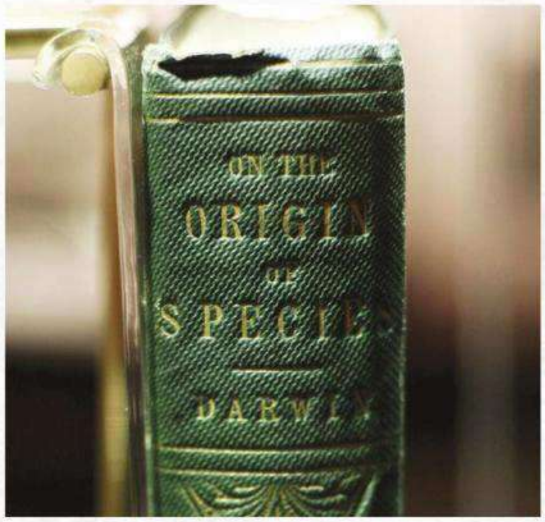
MICHAEL FARADAY

1791-1867

Chemist and physicist

FAMOUS THEN FOR: MAKING ELECTRICITY OUT OF MAGNETISM
FAMOUS NOW FOR: FARADAY CAGE

Let's be honest: many of us know Stephen Hawking for his appearances on *The Simpsons*, *Star Trek: The Next Generation* and *The Big Bang Theory*. We know him, simply, for being Stephen Hawking. He was, in the nicest possible sense, a bit of a show-off. The Victorian scientist Michael Faraday also knew how important it was to put on a good show, though his personality meant that it didn't come naturally to him. It was by watching the charismatic chemist Humphry Davy's public lectures that Faraday saw how it could be done. Capitalising on a chance opportunity to work for Davy, he built up to giving celebrated demonstrations of his own at the Royal Institution. He practised and practised his experiments – of which the Faraday cage (pictured above) remains the best known – until they could be presented flawlessly. Off-stage, he remained rather humble, rarely dining out with fellow public figures. His pledged aim was not his own fame, but to reveal God's laws at work in nature; unlike Hawking, he was a fervent Christian believer.

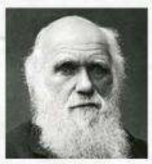


CHARLES DARWIN

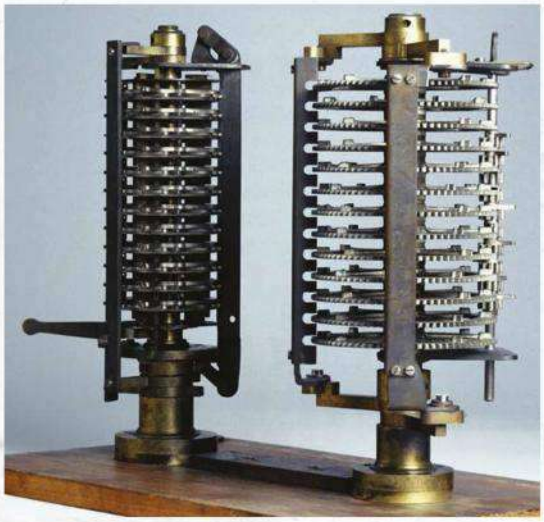
1809-1882

Naturalist

FAMOUS THEN FOR: EVOLUTION
FAMOUS NOW FOR: EVOLUTION



Like Stephen Hawking, Charles Darwin suffered lifelong illness. Nobody knows for sure what it was; theories about the cause range from a tropical parasite to his own psychology – perhaps anxiety about the upset his work in progress, *The Origin of Species*, was bound to cause. Whatever the reason, he groaned, sweated and shivered, keeping a vomit bowl close to hand. It was frequently a miserable existence for Darwin. Like Hawking, however, the bearded Victorian patriarch had a keen sense of fun, suffering his children to surf down the stairs on a tea-tray while he was writing. Both men appear to have shared a childlike approach to their research: a fascination with the quirks of nature and a pleasure in discovering the oddities of her ways. Darwin always had an instinct for the simple experiment, or the fearless guestimate, to test some theory of nature. On one famous occasion, this extended to engaging his son to play the bassoon to earthworms in order to test their sense of hearing. There was certainly something of Edward Lear's sensibility about him. Besides their shared senses of humour, Hawking and Darwin are perhaps also connected by the mischievous pleasure they both took in demonstrating that God's ways are not as rational as some might presume.

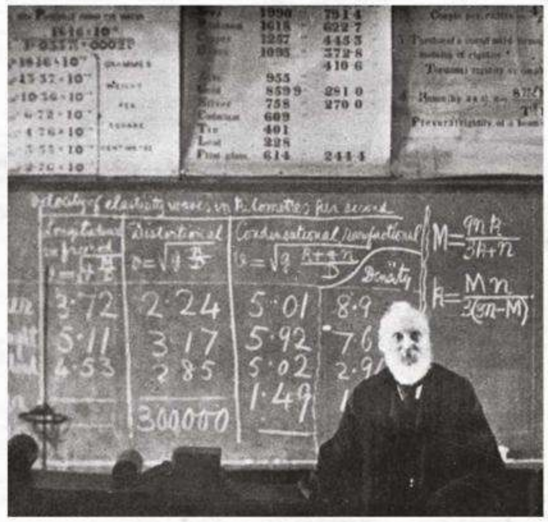


ADA LOVELACE
1815–1852

Mathematician

FAMOUS THEN FOR: BEING BYRON'S DAUGHTER
FAMOUS NOW FOR: BEING A FEMALE PIONEER OF COMPUTING

Ada Lovelace was quick to identify that Babbage's Analytical Engine (parts of which can be seen above) could be used to compute a mathematical function "without having been worked out by human head and hands first". And from her advanced understanding of mathematics proposed the kind of equations that it could be set to process. This has retrospectively been identified as the germinal moment of computing science – the insight that a calculating engine could run more than one task. Lovelace is an example of a historiographically questionable but culturally worthy phenomenon: combing through the past to find the heroes we need. Lovelace wins on two counts: she has been identified as a precursor to a relatively new science that required a history, and she was female. It's not, perhaps, reasonable or productive to measure her against her male contemporaries. She may have been more talented than many, but her achievements were bound to be less; her life was constrained by her gender and cut short by an early death from cancer.



WILLIAM THOMSON (LORD KELVIN)
1824-1907

Physicist

FAMOUS THEN FOR: PREDICTING THE DEATH OF THE SUN
FAMOUS NOW FOR: THE KELVIN SCALE OF TEMPERATURE

Thomson thought on a cosmic scale, striking a fine balance between physics and philosophy. His aim was to unify physics with a single theory to account for the actions of electricity, magnetism, heat and even matter – and more difficult still, to unify all this with the purposes of the Christian God. Raised a Calvinist Presbyterian, he could not help but see the dissipation of energy in the Universe (his second law of thermodynamics) as a feature of the fallen world. God had made energy, and it was the duty of humans to try and prevent decay and waste wherever they saw it. He was a model of hard work and wealth generation, gaining riches from his 70-plus technical patents, particularly in the growing field of telegraphy. Yet the big questions continued to bug him; towards the end of his life his insistent re-calculations of the age of the Sun and Earth began to look a little like an idée fixe to the next generation of physicists. Though Thomson's estimated date for the Sun's demise lay reassuringly far in the future, it spawned an array of alternative calculations that made fin-de-siècle Victorians fear the end was literally nigh.

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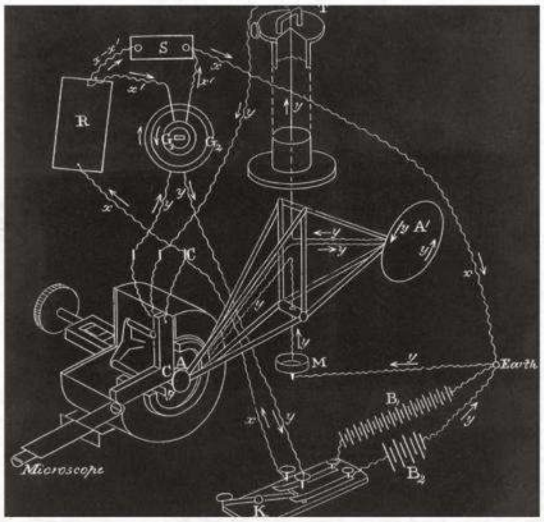
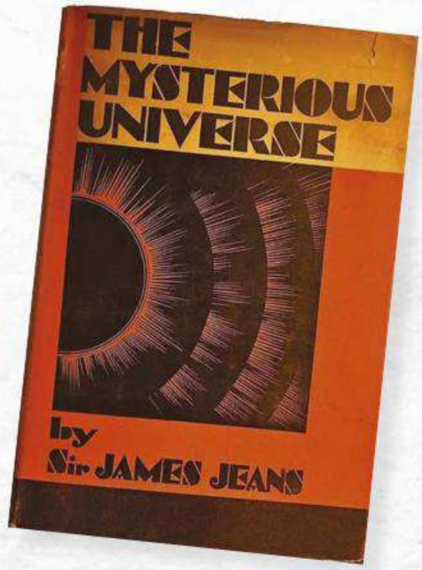
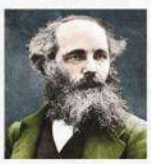




JAMES CLERK MAXWELL
1831-1879

Physicist

FAMOUS THEN FOR: UNIFICATION OF PHYSICS
FAMOUS NOW FOR: MAXWELL'S DEMON



Almost completely unknown by the public today, James Clerk Maxwell was a towering figure in the world of science, achieving what was considered to be the second great unification of physics after that accomplished by Newton. Newton had shown that mechanics worked the same on Earth and in the heavens; Maxwell swept up light into a single model of thought with electricity and magnetism (a diagram of instruments needed to accomplish this is pictured above). In this sense, he stands alongside Hawking, who advanced upon the challenge of unification in physics today: relativity, quantum mechanics and thermodynamics. Part of the problem for Maxwell's reputation was that it came rather late. He was internationally known in the final decade of his life, but the agreed vindication of his theories came posthumously. Nor did he see himself as a professional scientist, though such a career possibility had emerged by the end of his life. His preference, expressed in his writings, was for a gentlemanly form of science. His equations' essential role in enabling media technologies of the 20th century has gone unsung and he would probably prefer it to remain that way.

JAMES JEANS
1877-1946

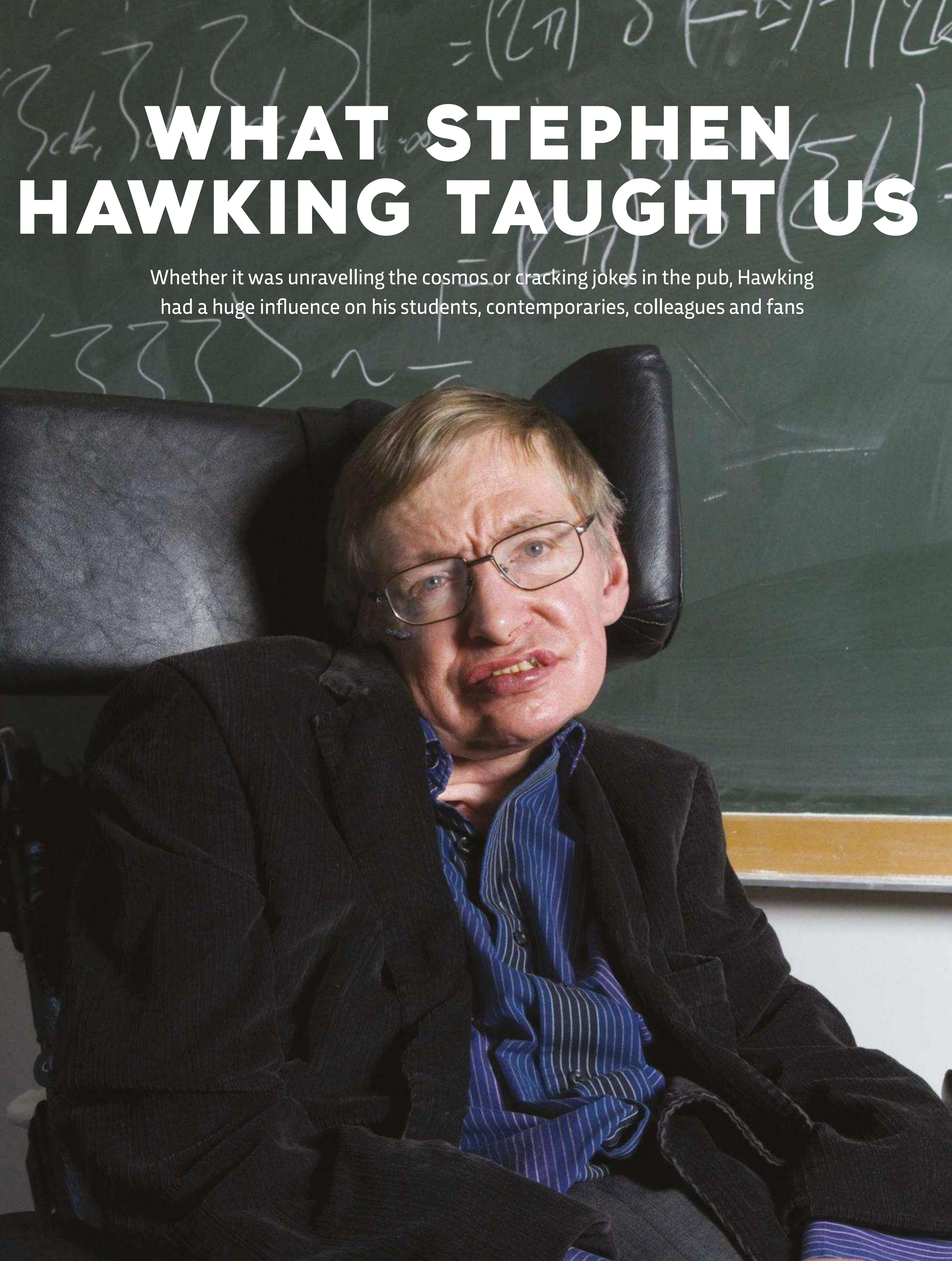
Mathematician and astronomer

FAMOUS THEN FOR: WRITING THE MYSTERIOUS UNIVERSE
FAMOUS NOW FOR: BEING WRONG

During the 1920s, popular interest in physics exploded. The new BBC put science lectures at the forefront of its mix of programmes, and a host of magazines and paperbacks catered to the public's fascination. Einstein's recently conjured science of relativity was a frequent topic of discussion. James Jeans, having amassed great honour in his research on radiation and quantum theory, became the public voice of relativity and other topics in physics and cosmology. In the process, he acquired more honour and accolades – a veritable Hawking of his day. Jeans's bestseller *The Mysterious Universe* hit a sweet spot in the public's appetite for theological and cosmic speculation, much like *A Brief History of Time*. Jeans's personality was rather arrogant and sarcastic, and it's difficult to imagine him succeeding in today's media culture. In the mid-20th century, however, it was all in keeping with the persona of the great scientist. In his later research, Jeans proposed a steady-state account of the Universe, which not long after his death was swept aside by Big Bang theory. Rather quickly and completely, his reputation dissipated. Heroism in science can be a brutal business.

WHAT STEPHEN HAWKING TAUGHT US

Whether it was unravelling the cosmos or cracking jokes in the pub, Hawking had a huge influence on his students, contemporaries, colleagues and fans



DR LEONARD MLODINOW

The physicist and author wrote books with Stephen Hawking. His latest book is Elastic: Flexible Thinking in a Constantly Changing World

"It was striking how Stephen didn't let anything go. We'd argue over individual words. He'd have to go through a lot of work to present his side, but he never gave up. He'd say himself that his best and worst quality was his stubbornness. I don't think he could have gotten through life if he wasn't so stubborn.

I remember the night we finished *The Grand Design*. We'd been working on it for four years. He showed no sign of wanting to finish. We kept pushing the deadline. I think we were supposed to take a year and a half but finally the publishers just said, "we're announcing it, so we're going to publish it, finished or not." I remember thinking I'm going to have to pay back the advance somehow. If ever I suggested moving on from a chapter, he'd always say: "No, it doesn't matter when it's done, as long as it's good." We literally finished at the last minute, at 8pm on the deadline. I remember we even had a little fight over something in the last few hours. But he kind of steered the ship on that so we'd agree on the final point at the last moment. I was so relieved. I couldn't believed we'd made it. Then he turns to me and says: "Good thing we had the deadline or I would never have stopped."

His other major quality was humour. He had that really big smile. His face was very expressive. He had expressions to say yes and no. He also had what we'd call a steely look of disdain if he really didn't like what you'd said. Sometimes he'd hit the wrong thing on his computer and a random sentence would come out. I think it was some cache unloading, but you'd ask him something simple like, "Where shall we go for dinner?" And the answer you'd get would be something like: "The treefrog of the supernova exploded in Aristotle."

Another good story was the time one of his carers invited me to go punting down the Cam. I asked Stephen if he wanted to come, thinking it was a longshot, and he said sure. When we arrived we found a long trail of stone steps leading down to where the boats launch. So we had to park his chair at the top and carry him down. I started carrying him, but the carers didn't like the way I was holding him. I think I had his head in the wrong place. So these two carers probably about 95lb (43kg) each – I'm something like 185lb – give me their purses to hold and they start carrying Stephen down to the river with me just holding their purses. When we get there they just give me the stick as I get in the boat and then tell me that the boats can tip over if you're not careful. So I'm there thinking if this tips over, he's dead. I could kill Stephen Hawking. But he's fine, just sitting there smiling. He was so intrepid.

We wrote about physics because it was just so beautiful. I thought that everyone would love it if they could just understand what we were talking about. I think Stephen felt the same way. I mean, Stephen didn't think *A Brief History of Time* was very clear. That's why we wrote *A Briefer History of Time* together. He described it as the most bought and least read book of all time.

The movie *The Theory of Everything* was "broadly accurate", as Stephen put it, which people took as an endorsement. But I know Stephen. When he says that, he also means, not necessarily accurate in the details. That was a perfect Stephenism. One of the details that bugged me was the moment he gets the idea for Hawking radiation. We know that he struggled with this for months, years and, at times, would get depressed over it. But in the movie he gets the idea staring into a fireplace, seeing some ember explode, then it cuts to everyone's clapping. But it doesn't work that way. It comes back to his stubbornness."

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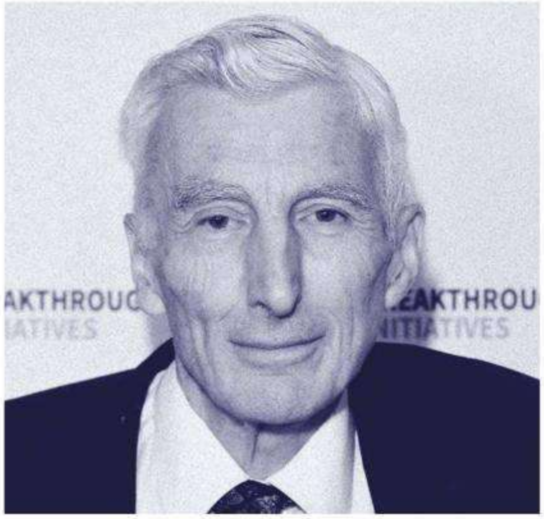

LORD MARTIN REES

Astronomer Royal, cosmologist and astrophysicist

"I was two years junior to Stephen and joined the research group in Cambridge when he was already working on his PhD. I got to know him at the time when he found out that he had motor neurone disease. By that point he was already walking slowly with a stick.

At that time Stephen's life expectancy was very short – many people didn't think he'd even be able finish his PhD. As Stephen himself later said, when he did finish his PhD and got married, his gloom lifted – he realised that he did have prospects.

He clearly had great mathematical ability, insight and great determination. I think scientifically he'll rate as one of the key people who has pushed forward our understanding of gravity in the last half century. In particular, for helping us understand black holes better.

The paper he wrote in 1974, the so-called 'Black Hole Explosions' paper, was important as the first quantitative attempt to link Einstein's Theory of General Gravity with the micro world of the quantum theory. That paper has implications that are still being debated today.

Another breakthrough came when his book, *A Brief History of Time*, which was published in 1988, became a huge bestseller – to his and everyone else's surprise.

That catapulted him to international stardom and people became interested in him as a personality, someone who, despite being imprisoned in an increasingly helpless body, was roaming the cosmos. This also gave him a further stimulus to engage in outreach events.

I think everyone can learn from Stephen that there are huge satisfactions to be gained from doing science and that even someone with his disadvantages is able to lead a full and varied life. The subject that he chose to study is still immensely challenging and fascinating to a younger generation who will follow and build on his work.

Throughout his extraordinary life Stephen remained extraordinarily normal, in that, despite his immensely frustrating disabilities – especially in the difficulty it created for him in communicating – he maintained wide interests in music and theatre. He travelled to exotic places and committed to various causes, including nuclear disarmament, the Palestinians and the National Health Service in particular.

I think Stephen had a good start in that he and I were both supervised by Dennis Sciama, who was a very inspiring supervisor. He had a very broad feel for the subject, both observational and theoretical and he gave us all good advice.

The advice Dennis gave to Stephen was that he should go to London to listen to a lecture by Roger Penrose, who had been developing new mathematical techniques that allowed him to consider gravitational collapse when there was no special symmetry. Stephen went to these lectures and his early papers, some of them written with Roger Penrose, used these techniques. So, he was fortunate to have a stimulus from Roger Penrose who was a great figure in the subject and he was also fortunate that this was the time when observations were revealing the first evidence for the Big Bang and the first evidence for black holes so this was a good time for young people to be starting in the subject

Stephen was also lucky in that he was going into a subject that was opening up and required talents well matched to those he had."

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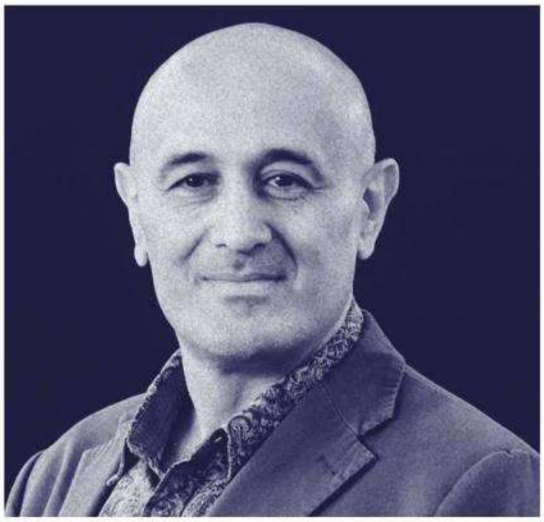
EVEREST
John Evelyn
GALTON



JIM AL-KHALILI

Recipient of the inaugural Stephen Hawking Medal for Science Communication

"I think the first time had a conversation with Stephen was in 2010 or 2011. He gave a lecture at the Royal Albert Hall and I was asked to introduce him. When I started talking to him I hadn't realised that he would twitch his cheek muscles to say no and his eyebrows to say yes. If you don't know he's responding you sort of fill in the gaps by blabbering on yourself. Afterwards his nurse asked: "Have you spoken to Stephen before? Did you know what he was saying?" When I told her I hadn't, she said: "Well, there were lots of yesses and nos in there but as you were talking you probably missed them."

The lecture he gave that night was incredible. There were about 6,000 people in the audience but for the hour and a half that he talked about cosmology and his life you could have heard a pin drop. He could have just played a recording of his voice but he was obviously adamant not to be impersonal. He had to activate his voice synthesizer to start each paragraph so he was giving a live performance rather than just sitting there on stage, immobile.

The second time I met him was when he presented me with the inaugural Stephen Hawing Medal. I was very honoured. There were a lot of big names in science there. It was quite something. Apparently he chose me as he'd watched my TV series on quantum physics.

It was very strange. If you think about it, the medal for science communication should have gone to Stephen Hawking. In as much as *A Brief History of Time* is said to have sold more copies than the Bible. I still work as an admissions tutor in the physics department of physics at the University of Surrey, so I read all the personal statements and invariably the students were switched on to physics because they read *A Brief History of Time*. I might make a TV documentary and so on, but I'm not reaching and inspiring anything like the number of people Stephen has. Just doing *The Simpsons*, for goodness sake, reaches out to areas of society that anyone else in this world couldn't do. So it meant a lot to me to get that award and to have Stephen present it. It was pretty special.

I think Stephen changed the rules of the game when it came to communicating science to a wider audience. I remember, I was an undergraduate in the 1980s, before *A Brief History of Time* came out. There were science popularisers about – John Gribbin, Frank Close, Paul Davies, John Barrow – but popular science books were niche. They were there for the people who were interested in science, people who looked out for them. When *A Brief History of Time* came out everyone wanted a copy on their coffee table, even if they didn't read it. And since then, there's been this explosion in science communication and in the respectability that science communication got. Until then you were either the scientist who does the research and wins Nobel Prizes or you were the communicator. There were very few people – maybe Richard Feynman and one or two others – who excelled at being both great thinkers and great explainers. Hawking was the great thinker and explainer of our generation.

Stephen made it possible for people to think: "I want to do the science, but I also want to explain it to other people." And that doing so is a valid, respectable pursuit. Until then it was a case of: if you're smart, you do the smart stuff – the research and experiments. Leave the communicating to those who can't do the smart stuff, as though it's a lesser thing. Stephen changed that. In terms of communicating he changed the game; he became the most famous scientist since Albert Einstein.

Any publisher will tell you that *A Brief History of Time* changed the game. He made books about the nature of space and time cool."

ALAMY, JIM AL-KHALILI

"I think Stephen changed the rules of the game when it came to communicating science to a wider audience"

BBC, BRAM SAEYS

DR CHRISTOPHE GALFARD

Writer, science communicator and former PhD student of Prof Stephen Hawking

"I was Prof Hawking's PhD student from 2000-2006. I wasn't daunted by his celebrity – in the academic world, that's kind of irrelevant – but what was daunting was that he was extremely hard to work with, in the sense that he only wanted to tackle the big questions: the hardest problems in theoretical physics.

He had a rare intuition that I think only a handful of scientists every century possess: he could see beyond the maths to the bigger picture. I worked with him on a type of string theory called M-theory and on the black hole information paradox, where black holes seemed to be leaking information from the Universe. Each time I showed him some new results, he would immediately know where to point the finger.

His philosophy was to spend as much time as possible with his colleagues and students. He didn't do scientific small talk, but he was always lively to be around. He'd joke and talk about movies and which restaurants to check out – he'd take us out to dinner for our birthdays. He was generous with his thoughts and his time, and his joy of life.

It's always when you're at the start of something that it's the most fulfilling – when you're just beginning to understand things, and there's someone there to hold your hand and show you the way. He was that person for me, and the six years I spent with him were probably the richest and fullest of my life."

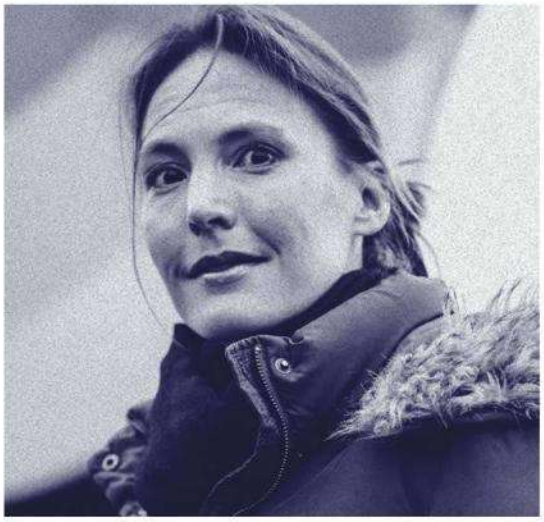
PROFESSOR MARIKA TAYLOR

Theoretical physicist at the University of Southampton and former PhD student of Prof Stephen Hawking

"I first met Stephen in 1995 to discuss options for my PhD. I was nervous, but he jumped straight into a conversation about physics and sent me away with a list of papers to read about string theory. He was already a celebrity by this point. When I was an undergraduate, he was living in a flat behind my student house, and friends would come to my room just to get a glimpse of him.

Because of his medical issues, Stephen couldn't work problems out on paper. So his PhD students were really important to him – they'd help do the calculations and develop his ideas. By working with Stephen, we were dragged right to the forefront of research.

During lunch, the conversation would drift into politics, movies and music. He had broad tastes – he liked arthouse films, but I remember him saying how much he enjoyed *Babe* – the movie about the talking pig. He had a wonderful smile, and because he was forced to communicate so concisely with his synthesiser, he had a gift for one-liners. Once, we were sitting in a pub and he suddenly turned up the volume on his synthesiser and announced "I'm coming out". He was referring to a change of mind he'd had on the black hole information paradox, but he clearly enjoyed winding up the entire pub. I'm going to miss his sense of warmth and his humour – he was full of ideas, enthusiasm and spark."



DR HELEN CZERSKI

Physicist and BBC Focus columnist whose most recent TV series was Colour: the Spectrum of Science

"I was given *A Brief History of Time* when I was young. What I found so interesting was how clear Stephen was able to make all these weird and difficult ideas – they suddenly just made sense. I think when I was growing up I never thought things like time dilation and the gravitational weirdness you get in general relativity seemed strange because the first time I'd come across them they'd been so clearly explained. It was a huge start for me.

Of course, it wasn't the only book available on those topics but it was brief and it laid out simple geometrical arguments that made sense if you followed them and it made everything later easy. Everything is easy once someone has explained it properly and he explained it properly. That was a very important foundation to build on later.

Not all good scientists are good communicators. But there's a very strong history that started in places like the Royal Institution where people stood up and said what they thought. Hawking was part of the tradition – him, Richard Feynmann, Carl Sagan and people like that… There's a long list of people who thought so clearly that they could communicate in a very straightforward fashion. I think the key to great science is the same as the key to great communication: thinking clearly about what you're doing and prioritising your ideas. When those two things come together you have something that's very powerful.

I actually don't like the term science communication because it sounds as though you talk a foreign language and have to translate what's going on. Communication is the wrong word; it's about sharing – sharing your ideas and your enthusiasm. Communication makes it sound as if you're standing on a hill with semaphore flags trying to convey this very complicated thing. Science is all about sharing; scientists share ideas all the time. It's built into the discipline. The habit of sharing ideas with the public has been lost in the past few decades. It used to be very common. If you look at the Victorian era they shared their science all the time. Largely because that's how scientists got paid. I don't think of myself as a science communicator. I'm not an emissary from a weird world; I'm just talking about my perspective on the world and what I and others have learned about the way it works from the evidence we've uncovered.

Science is possibly the greatest collective endeavour of humanity. The things we know about the world now have come from thousands of scientists over many generations each building on those that have gone before. We build on that knowledge. That's how it works. The problem is that people invent a barrier that isn't there. Stephen Hawking didn't see that barrier – he just got on with sharing what he knew.

As his life went on he played many different roles. He was a humanist; he didn't believe in the afterlife; he was a strong defender of community and the NHS. He made a lot of contributions to how we could think about things besides science. There's a perception that science is somehow separate from society and he showed very clearly that that is not the case.

Stephen was such a distinctive voice. If you asked anyone anywhere to name a scientist, I think his name would come up more often than any other. What made him so great was that he didn't just do one thing. He did the brilliant science, he did the brilliant communication, but he did other things as well, and all while dealing with considerable personal difficulties. He was by no means a perfect person; he was a human and had flaws like the rest of us. But he showed that it's possible to be many things, and opened doors for others to follow."

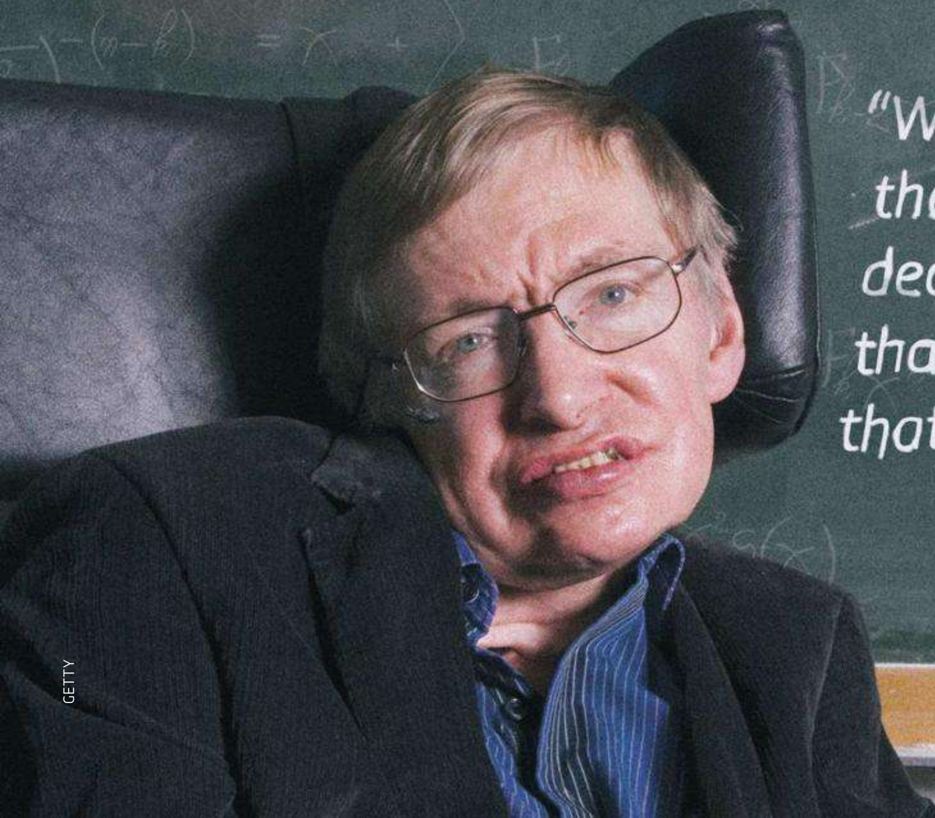
STEPHEN HAWKING IN HIS OWN WORDS

"It would not be much of a Universe if it wasn't home to the people you love."

"God may exist, but science can explain the Universe without the need for a creator."

"My goal is simple: it is a complete understanding of the Universe, why it is as it is and why it exists at all."

"I want to show that people need not be limited by physical handicaps as long as they are not disabled in spirit."



GETTY

"When you are faced with the possibility of an early death it makes you realise that life is worth living and that there are a lot of things you want to do."


PINT OF
SCIENCE

"Look up at the stars and not down at your feet. Try to make sense of what you see, and wonder about what makes the Universe exist. Be curious."

STEPHEN HAWKING

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